The Influence of Marine and Hydro Kinetics Patents Funded by the U.S. Department of Energy's Water Power Technologies Office and Other DOE Offices

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

Report prepared by:

1790 Analytics LLC
130 North Haddon Avenue
Haddonfield, NJ 08033

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Executive Summary

This report describes the results of an analysis tracing the technological influence of Marine and Hydrokinetic (MHK) research funded by the U.S. Department of Energy (DOE)'s Water Power Technologies Office (WPTO) and its precursor programs, as well as MHK 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 WPTO-funded MHK research has formed a foundation for innovations patented by leading MHK organizations. Meanwhile, the primary purpose of the forward tracing is to examine the broader influence of WPTO-funded MHK research upon subsequent technological developments, both within and outside MHK technology. In addition to these WPTO-based analyses, we also extend many elements of the analysis to other DOE-funded MHK patents, in order to gain insights into their influence.

The main finding of this report is:

- MHK research funded by WPTO, and by DOE in general, has had a notable influence on subsequent developments, both within and beyond MHK technology. This influence can be seen on innovations associated with the leading MHK companies. It can also be traced to innovations in other technologies, notably wind energy and hydropower.

More detailed findings from this report include:

- In MHK technology, in the period 1976-2018, we identified a total of 5,566 patents (1,877 U.S. patents, 1,335 EPO patents and 2,354 WIPO patents). We grouped these patents into 3,892 patent families, where each family contains all patents resulting from the same initial application (named the priority application).

- 49 MHK patents are confirmed to be associated with WPTO funding (30 U.S. patents, 5 EPO patents, and 14 WIPO patents). We grouped these WPTO-funded MHK patents into 24 patent families.

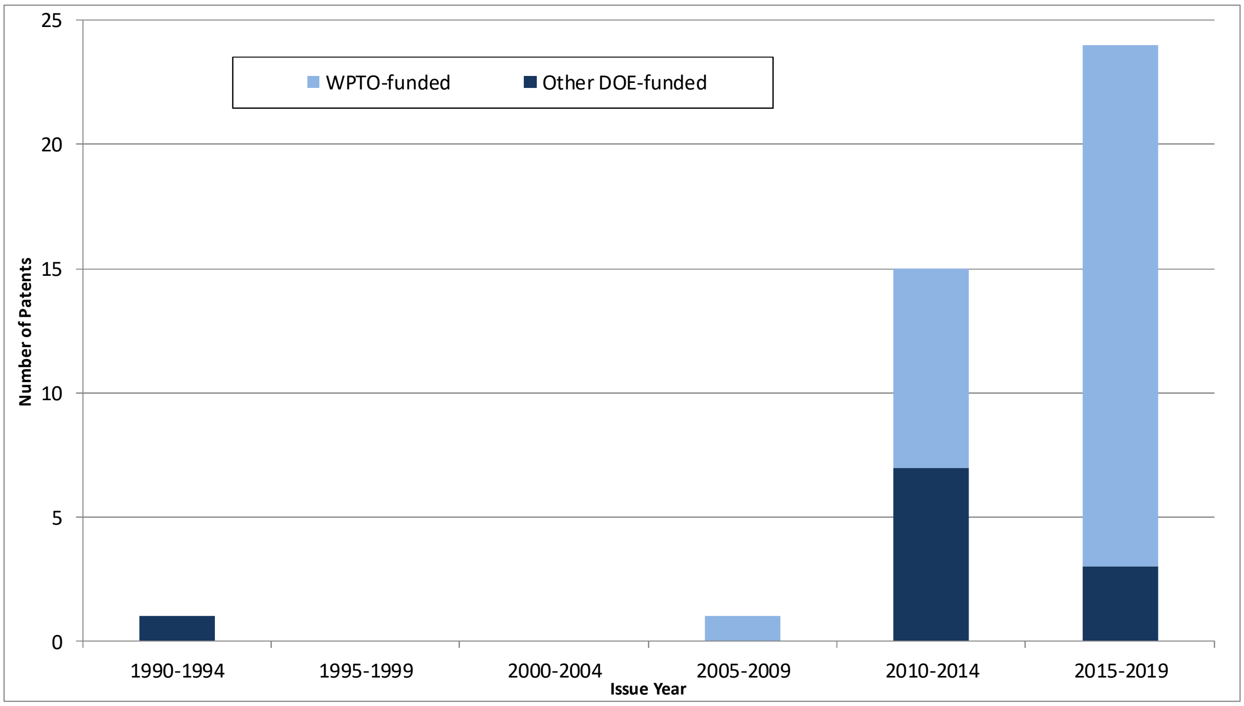
- In addition, we identified a further 21 MHK patents (11 U.S. patents, 4 EPO patents and 6 WIPO patents) that are associated with DOE funding. These "Other DOE-funded" patents are grouped into 11 patent families.

- The total number of DOE-funded MHK patents (WPTO-funded plus Other DOE-funded) is 70, corresponding to 35 patent families. This represents 0.6% of the total number of MHK patent families in the period 1976-2018.

- Figure E-1 shows the number of WPTO-funded and Other DOE-funded MHK U.S. patents by issue year. There was only one Other DOE-funded patent granted in 1990-

1994 and one WPTO-funded patent granted in 2005-2009, with no patents between these periods. The number of DOE-funded MHK U.S. patents then increased to fifteen in 2010-2014, with eight of these patents funded by WPTO. DOE-funded patents increased again to 24 in 2015-2019 (21 of them WPTO-funded), even though data for this time period are incomplete (see note below Figure E-1). This figure thus suggests that DOE-funded MHK patenting occurred primarily in the most recent time periods in the analysis, with WPTO-funded patents representing an increasing percentage of these patents over time. This parallels WPTO's specific funding of MHK technology, which is also concentrated in the most recent time periods covered by the analysis.

Figure E-1 - Number of WPTO/Other DOE-Funded MHK 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, or were supplied directly by WPTO. No new patent search for 2019 was carried out.

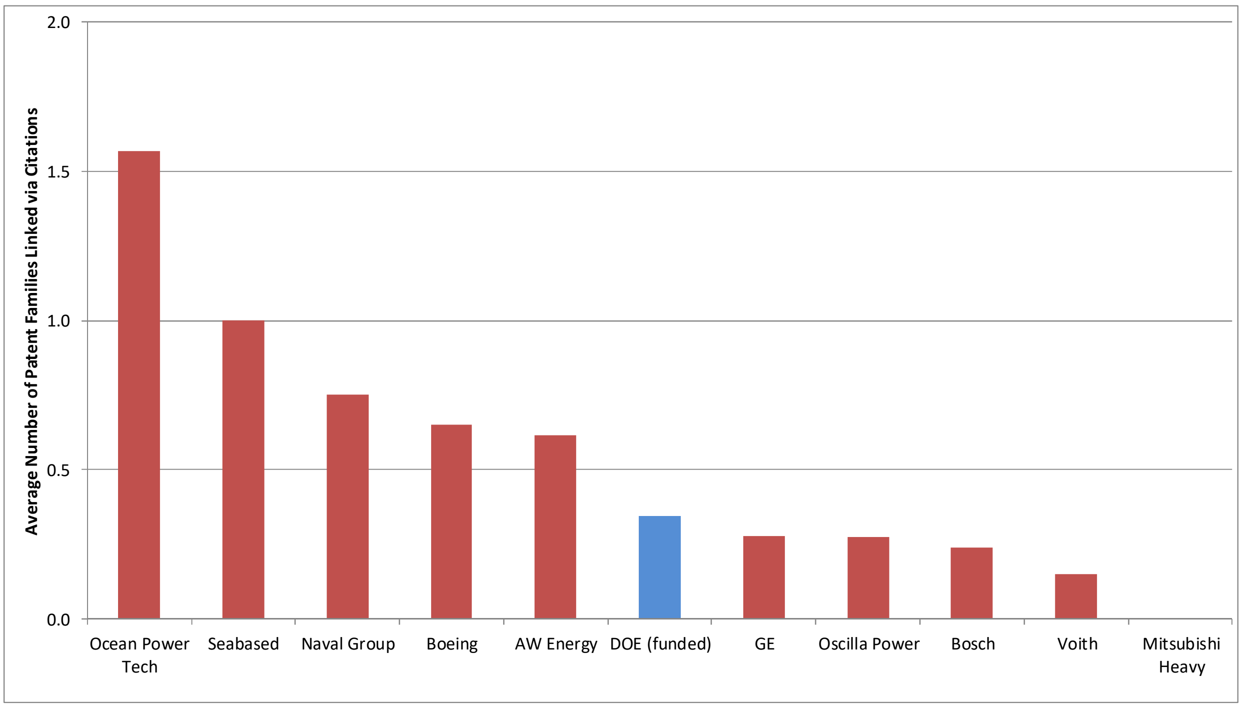
- The ten companies with the largest MHK patent portfolios are: Ocean Power Technologies (65 patent families); Voith (61); General Electric (54); Bosch (42); Naval Group (40); AW-Energy (39); Seabased (33); Boeing (23); Mitsubishi Heavy Industries (22); and Oscilla Power (22). In comparison, the portfolio of 35 DOE-funded MHK patent families (24 WPTO-funded and 11 Other DOE-funded) is in the middle of these portfolios in terms of size.

- WPTO-funded MHK patents have a particular focus on wave energy systems, submergible motors, and mountings for these motors. The leading companies, and MHK patents overall, also have a notable presence in these technologies. This suggests that WPTO-funded MHK research is aligned with research in MHK technology in general.

Meanwhile, Other DOE-funded MHK patents have a stronger focus on tidal stream power, an area where WPTO-funded patents have been largely absent in recent years.

- On average, DOE-funded MHK patent families (most of which are WPTO-funded) are each linked via citations to 0.34 subsequent patent families assigned to the leading MHK companies (see Figure E-2). This puts DOE sixth in Figure E-2. That said, it should be kept in mind that many of the DOE-funded (and particularly WPTO-funded) patent families are relatively recent, and so have not had much time to become linked via citations to subsequent generations of technology.

Figure E-2 - Average Number of Leading Company MHK Patent Families Linked via Citations to MHK Families from Each Leading Company
e.g. on average, each DOE-funded patent family is linked to 0.34 subsequent patent families assigned to leading companies

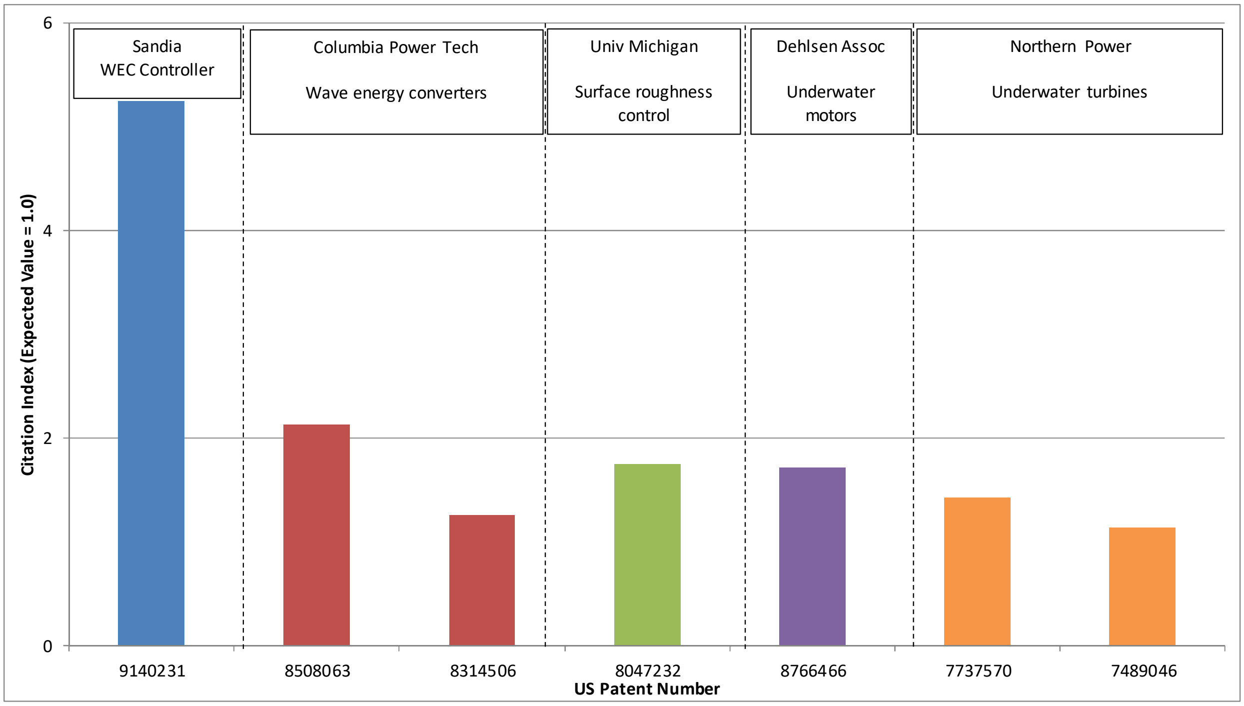


- Out of the leading companies, Boeing (through its ownership of Liquid Robotics), Oscilla, Bosch and Ocean Power Technologies have MHK patent families that are linked via citations to earlier WPTO-funded MHK patents. Meanwhile, Voith, General Electric and Bosch have MHK patent families that are linked to earlier Other DOE-funded MHK patents.

- WPTO-funded MHK patents have an average Citation Index value of 1.24 (the Citation Index is a normalized citation metric with an expected value of 1.0; a value of 1.24 shows that, based on their age and technology, WPTO-funded MHK patents have been cited as prior art 24% more frequently than expected by subsequent patents). This puts WPTO-funded patents fourth among the leading MHK companies. The Citation Index for Other DOE-funded MHK patents is lower at 0.96, but this still means that these patents have been cited around as frequently as expected. The influence of WPTO-funded and Other DOE-funded MHK patents has been primarily within MHK technology, but can also be traced in in other renewable energy technologies, notably wind energy and hydropower.

- There are a number of individual high-impact WPTO-funded MHK patents, examples of which are shown in Figure E-3. They include Sandia and Columbia Power Technologies patents for wave energy converters; a University of Michigan patent outlining surface roughness adjustment for fluid flow control; and patents describing underwater motors and turbines assigned to Dehlsen Associates and Northern Power Systems.

Figure E-3 – Examples of Highly-Cited WPTO-funded MHK Patents



1.0 Introduction

This report focuses on Marine and Hydrokinetic (MHK) technology. Its objective is to trace the influence of MHK research funded by the Department of Energy (DOE) Water Power Technologies Office (WPTO) – plus MHK research funded by DOE as a whole – on subsequent developments both within and outside MHK technology. The purpose of the report is to:

(i) Locate patents awarded for key WPTO-funded (and other DOE-funded) innovations in MHK technology; and

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

The primary focus of the report is on the influence of WPTO-funded MHK patents. That said, we also extend many elements of the analysis to DOE-funded MHK patents that could not be definitively linked to WPTO 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 WPTO itself upon the development of MHK technology, while also tracing the influence of DOE more generally. Meanwhile, in practical terms, determining which patents were funded by WPTO, 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 WPTO-funded, we instead included these patents in the analysis under a separate "Other DOE-funded" category.

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 WPTO-funded and Other DOE-funded patents. These results show the distribution of WPTO-funded (and Other DOE-funded) patents across MHK technologies (as defined by Cooperative Patent Classifications). They also evaluate the extent of WPTO's influence (and DOE's influence in general) on subsequent developments in MHK and other technologies. Patent level results are then presented to highlight individual WPTO-funded MHK patents that have been particularly influential, as well as to locate key patents from other organizations that build extensively on WPTO-funded MHK 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 MHK industry have used earlier WPTO-funded research as a foundation. Meanwhile, the primary purpose of the forward tracing is to examine how WPTO-funded MHK patents influenced subsequent technological developments more broadly, both within and outside MHK 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 MHK 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 MHK 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.

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

[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 WPTO-funded MHK patents and Other DOE-funded MHK patents. However, referring repeatedly to "WPTO-funded/Other DOE-funded patents" or "WPTO-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.

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 MHK research. Specifically, we identify cases where patents cite DOE-funded MHK 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 MHK patents. 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 MHK research. By determining how frequently DOE-funded MHK 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 MHK.

[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.

Forward and Backward Tracing

As noted above, the purpose of this analysis is to trace the influence of DOE-funded MHK research upon subsequent developments both within and beyond MHK 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 MHK 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 MHK organizations build on earlier WPTO-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 MHK patents resulting from research funded by DOE (i.e. WPTO plus Other DOE). The influence of these patents on later generations of technology is then evaluated. This tracing is not restricted to subsequent MHK 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 MHK 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 MHK 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 MHK 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 MHK 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 MHK patents and traces forward for two generations of subsequent patents.

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

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

1. **Direct Links**: where a patent cites a DOE-funded MHK patent as prior art.
2. **Indirect Links**: where a patent cites an earlier patent, which in turn cites a DOE-funded MHK 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 MHK patents, and also for the patents owned by leading MHK organizations. We also assembled families for all patents linked via citations to DOE-funded MHK 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 and WIPO patents, which are grouped in the same patent family because they share the same Japanese priority document.

[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.

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

3.0 Methodology

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

Identifying WPTO-funded and Other DOE-funded MHK Patents

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

(i) Defining the universe of DOE-funded patents;

(ii) Determining which of these DOE-funded patents are relevant to MHK; and

(iii) Categorizing these DOE-funded MHK patents according to whether or not they can be linked definitively to WPTO 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 MHK Patents

Having defined the universe of DOE-funded patents, the next step was to determine which of these patents are relevant to MHK technology. We designed a custom patent filter to identify MHK 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 MHK Patents

Filter A
Cooperative Patent Classification
F03B 13/12-268 – Machines/engines using wave or tidal energy
Y02E 10/38 – Wave or tidal swell energy
Filter B
Cooperative Patent Classification
F03B 17/06 – Machines/engines using liquid flow
Y02E 10/28-32 – Tidal stream or damless hydropower
AND
Title/Abstract
(wave* or tide* or tidal* or marine* or ocean*) +-3words (energy or power*)
river* +-3words current*
over(-)top*
oscillating(-)wave(-)surge(-)converter*
oscillating(-)water(-)column*

We manually checked this initial list of patents to determine which of them appear relevant to MHK, and then sent the resulting patent list to WPTO for review. Following this review, and based on feedback from WPTO, the initial list of MHK patents funded by DOE contained a total of 40 granted U.S. patents.

Defining WPTO-funded vs. Other DOE-funded MHK 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 40 DOE-funded MHK patents in the initial list could be linked definitively to WPTO 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 WPTO technology managers to verify individual patents,
(iv) Asking WPTO 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 WPTO, 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 WPTO-funded and Other DOE-funded MHK Patents

Based on the process described above, we divided the initial list of 40 DOE-funded MHK U.S. patents into two categories – WPTO-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 WPTO-funded and Other DOE-funded MHK patents and patent families.

Table 3 – No. of WPTO-funded and Other DOE-funded MHK Patents and Patent Families

	# Patent Families	# U.S. Patents	# EPO Patents	# WIPO Patents
WPTO-funded	24	30	5	14
Other DOE-funded	11	11	4	6
Total DOE-funded	35	41	9	20

Table 3 shows that we identified a total of 24 WPTO-funded MHK patent families, containing 30 U.S. patents, 5 EPO patents, and 14 WIPO patents (see Appendix A for patent list). We also identified 11 Other DOE-funded MHK patent families, containing 11 U.S. patents, 4 EPO patents, and 6 WIPO patents (see Appendix B for patent list). The bulk of these DOE-funded patents are relatively recent. This parallels WPTO's specific funding of MHK technology, which started during the 2010-2014 time period.

Identifying MHK Patents Assigned to Leading Organizations

The backward tracing element of our analysis is designed to evaluate the influence of WPTO-funded (and Other DOE-funded) research on MHK innovations produced by leading organizations in this technology. To identify such organizations, we first defined the universe of MHK patents in the period 1976-2018 using the patent filter detailed earlier in Table 2. Based on this filter, we identified a total of 1,877 U.S. patents, 1,335 EPO patents, and 2,354 WIPO patents. We grouped these patents into 3,892 patent families by matching priority documents.

We then located the most prolific patenting organizations in this overall MHK patent universe, based on number of patent families. The ten organizations with the largest number of MHK patent families are shown in Table 4.[6]

[6] All ten of these organizations are companies. For clarity, they are referred to in the results section of the report as the leading MHK 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 MHK companies, but this is a cumbersome description to use throughout the results section of the report.

Table 4 – Top 10 Patenting MHK Companies

Company	# MHK Patent Families
Ocean Power Technologies	65
Voith	61
General Electric	54
Bosch	42
Naval Group	40
AW-Energy	39
Seabased	33
Boeing	23
Mitsubishi Heavy Industries	22
Oscilla Power	22

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 MHK patent families of the ten companies in Table 4 form the starting point for the backward tracing element of the analysis.

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

4.0 Results

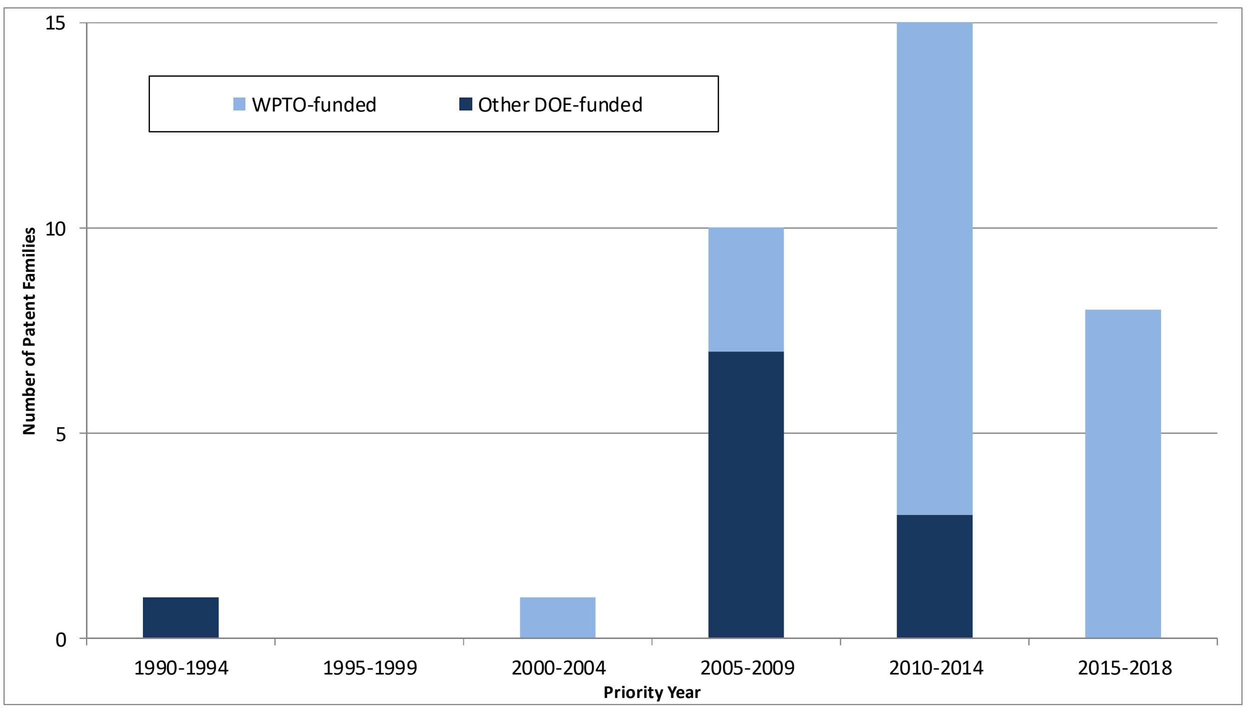
This section of the report outlines the results of our analysis tracing the influence of WPTO-funded and Other DOE-funded MHK research on subsequent developments both within and beyond MHK technology. The results are divided into three main sections. In the first section, we examine trends in MHK patenting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

Overall Trends in MHK Patenting

Trends in MHK Patenting over Time

Figure 1 shows the number of WPTO-funded and Other DOE-funded MHK patent families by priority year – i.e. the year of the first application in each patent family. WPTO-funded patent families are shown in light blue and Other DOE-funded families in dark blue. This figure reveals that there were only two DOE-funded MHK patent families filed prior to 2005 – a 1991 Other DOE-funded family and a 2004 WPTO-funded family. The number of DOE-funded MHK families then started to increase, with ten such families filed in 2005-2009 (three of which are WPTO-funded) and fifteen filed in 2010-2014 (twelve of which are WPTO-funded). The number of DOE-funded families fell to eight in 2015-2018 (all of them WPTO-funded), although data for this time period are incomplete (see note below Figure 1). Overall, there are 35 DOE-funded MHK patent families, 24 of which are WPTO-funded.

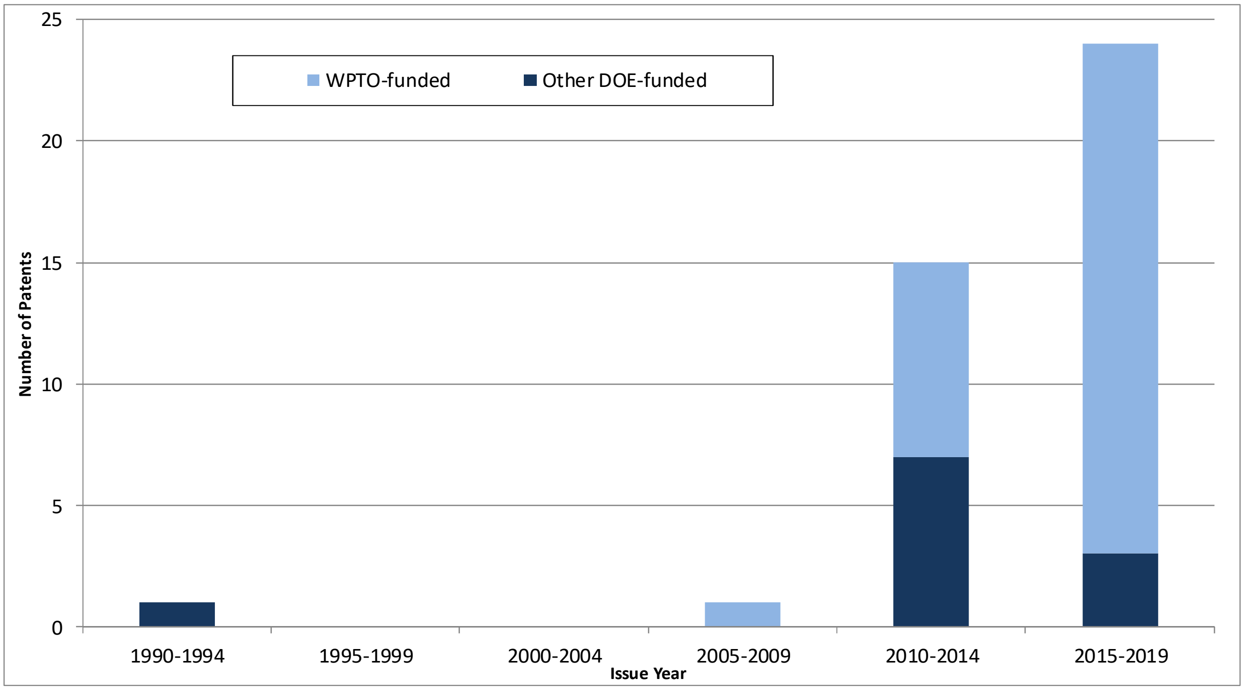
Figure 1 – No. of WPTO/Other DOE-funded MHK Patent Families by Priority Year (5-Year Totals)



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 1 suggests that DOE-funded MHK patenting is occurred primarily in the most recent time periods in the analysis, with WPTO-funded patents representing an increasing percentage of these patents over time. This pattern is also reflected in Figure 2, which shows the number of MHK granted U.S. patents funded by DOE in each time period. Here, there was only one patent in both 1990-1994 and 2005-2009, with no patents between these periods. The number of DOE-funded MHK U.S. patents then increased to 15 in 2010-2014, with eight of these patents funded by WPTO. The number increased further to 24 in 2015-2019 (21 of them WPTO-funded), even though data for this time period are incomplete (see note below Figure 2).

Figure 2–No. of WPTO/Other DOE-Funded MHK U.S. Patents by Issue Year (5-Yr Totals)

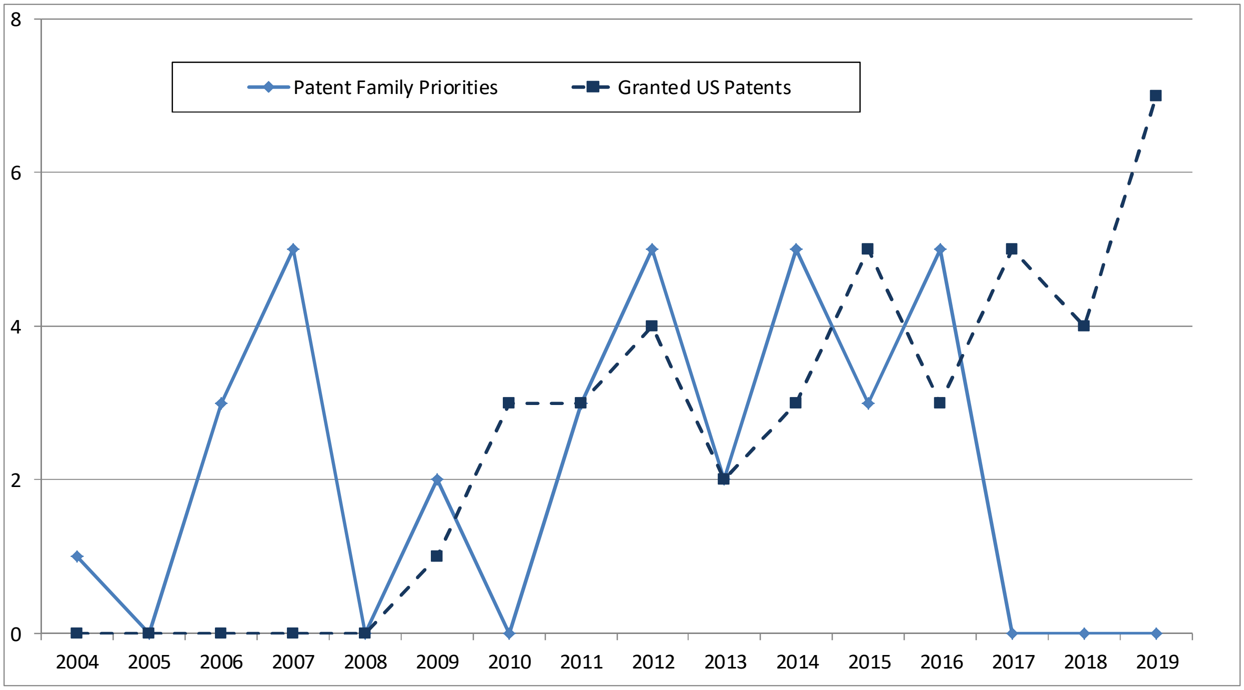


Note: The data collection period for this analysis ended with 2018. Any 2019 patents in the 2015-2019 column are additional patents that have been included because they are members of the same patent families as pre-2019 patents, or were supplied directly by WPTO. No new patent search for 2019 was carried 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 2005-2009 and 2010-2014 (Figure 1) resulting in granted U.S. patents in 2010-2014 and 2015-2019 (Figure 2). These time lags can also be seen in Figure 3, which shows MHK patent family priority years alongside issue years for granted U.S. MHK patents (in this figure, WPTO and Other DOE are combined, in order to simplify the presentation). Although trends in both data series in this figure are choppy, given the small numbers of documents involved, it is possible to see how a spike in patent families filed in 2007 led to U.S. patents increasing from 2010 onwards. More recently, patent family priorities dropped away after 2016, largely due to the primary data collection ending in 2018, although patents continued to be granted after that time.

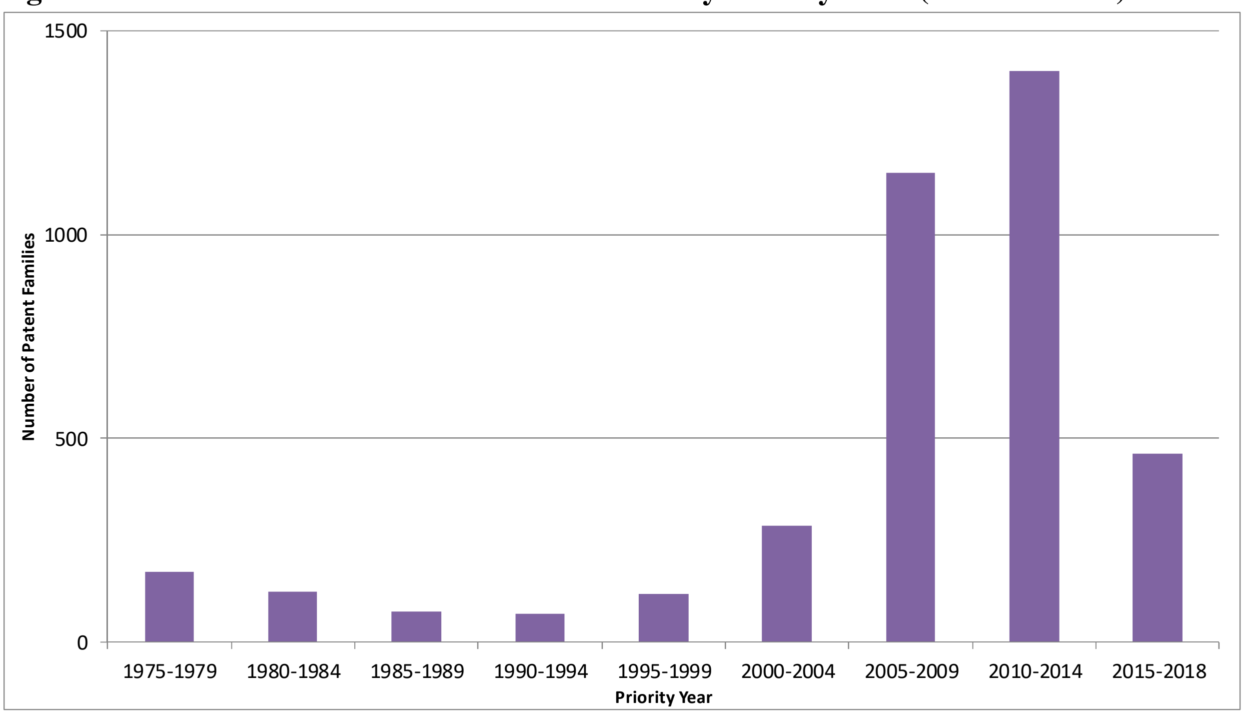
Figures 1-3 focus on DOE-funded MHK patent families. Figure 4 broadens the scope, and shows the overall number of MHK patent families by priority year (based on USPTO, EPO, and WIPO filings) from 1975 onwards. This chart reveals that 171 MHK patent families were filed in 1975-1979. The number then declined in the following time periods, reaching a low of 70 families in 1990-1994. After small increases in 1995-1999 and 2000-2004, the number of MHK patent families then grew sharply to 1,152 in 2005-2009 and 1,403 in 2010-2014. Hence, there were over twenty times as many MHK patent families filed in 2010-2014 as there were in 1990-1994. The number of MHK patent families then declined in 2015-2018, although data for this period are incomplete (see note below Figure 4).

Figure 3 - Number of DOE-funded MHK 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, or were supplied directly by WPTO. No new patent search for 2019 was carried out.

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

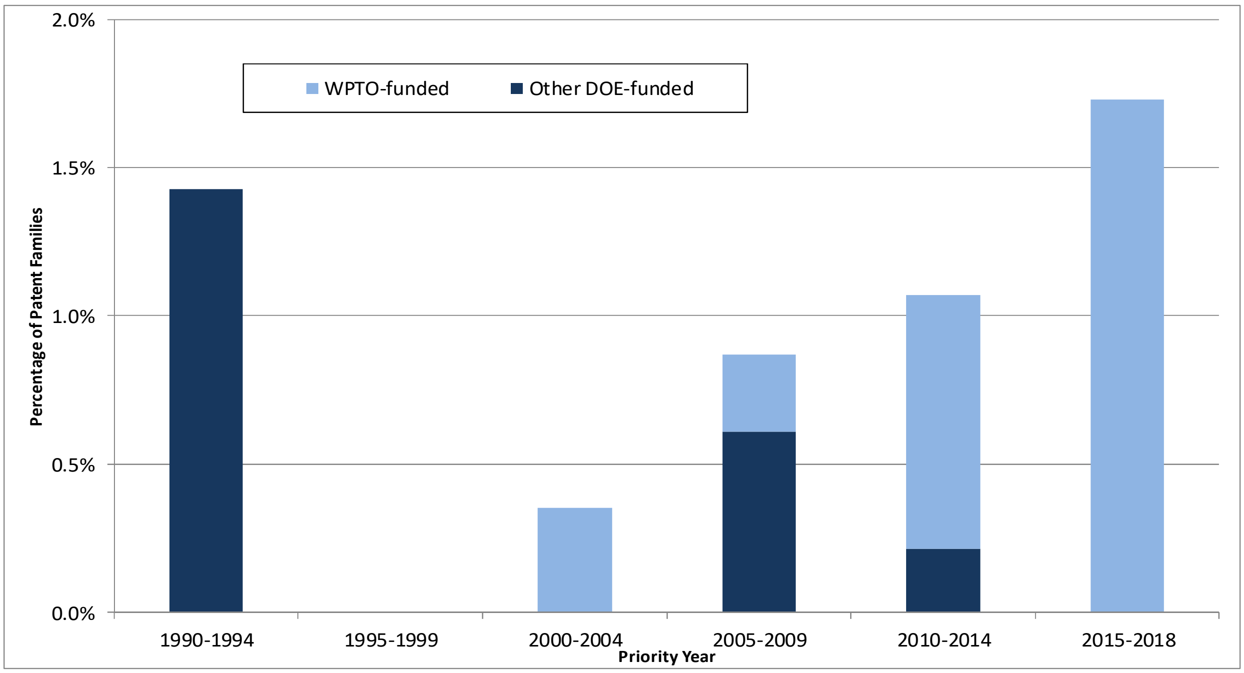


Note: The final time period in this figure is 2015-2018, and is shown for completeness, although data for this time period are incomplete. Our primary data collection covered only patents issued through 2018. Due to time lags associated with the patenting process, only a fraction of the patent families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

Comparing Figure 4 with Figure 1 suggests that the trend in DOE-funded (and WPTO-funded) MHK patenting is in line with the broader trend in this technology, with relatively little activity in the early periods in the analysis, followed by a sharp growth from 2005 onwards.

Figure 5 shows the percentage of MHK patent families that were funded by DOE (WPTO plus Other DOE). Leaving aside the column on the left-hand side of this figure (which is based on a single Other DOE-funded patent family), Figure 5 shows that DOE-funded patent families represent an increasing percentage of the total in recent time periods. In 2010-2014, more than 1% of all MHK families were funded by DOE (most of them by WPTO). This percentage increased to 1.7% in 2015-2018 (all of them funded by WPTO), although data for this time period are incomplete. Overall, 0.6% of MHK patent families in the period 1976-2018 were funded by DOE.

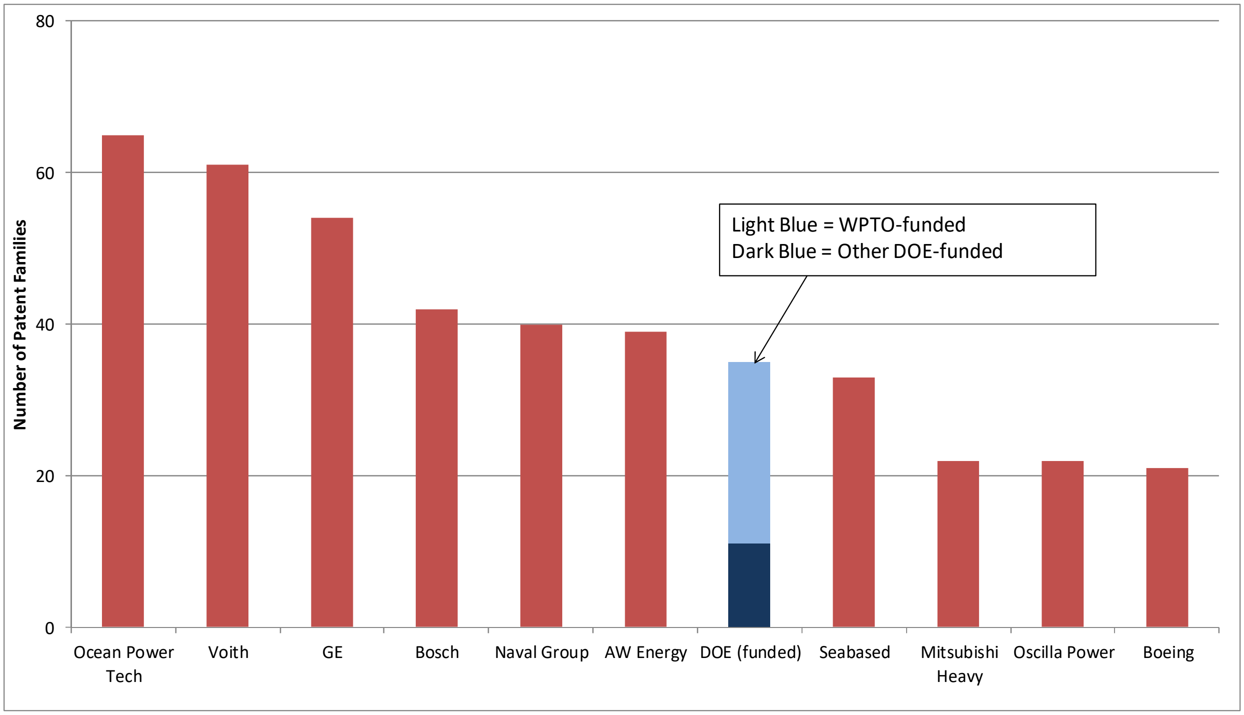
Figure 5-Percent of MHK Patent Families Funded by WPTO/Other DOE by Priority Year



Leading MHK Assignees

The ten leading patenting companies in MHK are listed above in Table 4, along with their number of MHK patent families. Figure 6 shows the same information in graphical form, while also including DOE-funded patent families. This figure is headed by Ocean Power Technologies with 65 MHK patent families, followed by Voith (61 families) and General Electric (54 families). All of the other companies in Figure 6 have fewer than 50 MHK patent families. It is interesting to note the geographical distribution of the leading MHK companies. Out of these ten companies, five are based in Europe, four in North America and one in Asia. Figure 6 also shows that the DOE-funded MHK portfolio of 35 patent families (24 WPTO-funded; 11 Other DOE-funded) is one of the smaller portfolios compared to the leading companies. In assessing the impact of WPTO-funded and Other DOE-funded MHK patents, versus the impact of the patent portfolios associated with the leading companies, we therefore take into account this difference in portfolio size.

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



It should be noted that there is a small amount of double-counting of patent families in Figure 6. Specifically, there is one Oscilla Power patent family that was partially or fully funded by WPTO. In Figure 6, this patent family is counted in both the WPTO segment of the DOE column, and in the Oscilla column. This double-counting is appropriate, since this patent family is both funded by WPTO and assigned to a leading company.

Assignees of WPTO/Other DOE-funded MHK Patents

The DOE-funded MHK patent portfolios are constructed somewhat differently from the portfolios of the top ten companies listed in Figure 6. Specifically, DOE's 35 patent families are those funded by DOE, but they are not necessarily assigned to the agency. For example, WPTO (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 Oscilla patent family discussed above).

Figure 7 shows the leading assignees on WPTO-funded patent families. This figure is headed by NTESS LLC (National Technology and Energy Solutions of Sandia), with four patent families resulting from its management of Sandia National Laboratory (SNL). It is one of two assignees associated with SNL in Figure 7, the other being Sandia Corporation, suggesting that SNL has been an important center for WPTO-funded MHK research. The other assignees in Figure 7 are Columbia Power Technologies (three patent families), Atargis Energy (two families) and the University of Michigan (two families).

Figure 8 shows the assignees on Other DOE-funded MHK patent families (since the number of such families is so small, all assignees are listed in this figure). This figure is headed by Ocean Renewable Power Company with four patent families, followed by Verdant Power (three families) and Georgia Tech Research Corporation (two families). The other two assignees in this figure – Brown University and Northeastern University – each have one Other DOE-funded MHK patent family.

Figure 7 - Assignees with Largest Number of WPTO-Funded MHK Patent Families

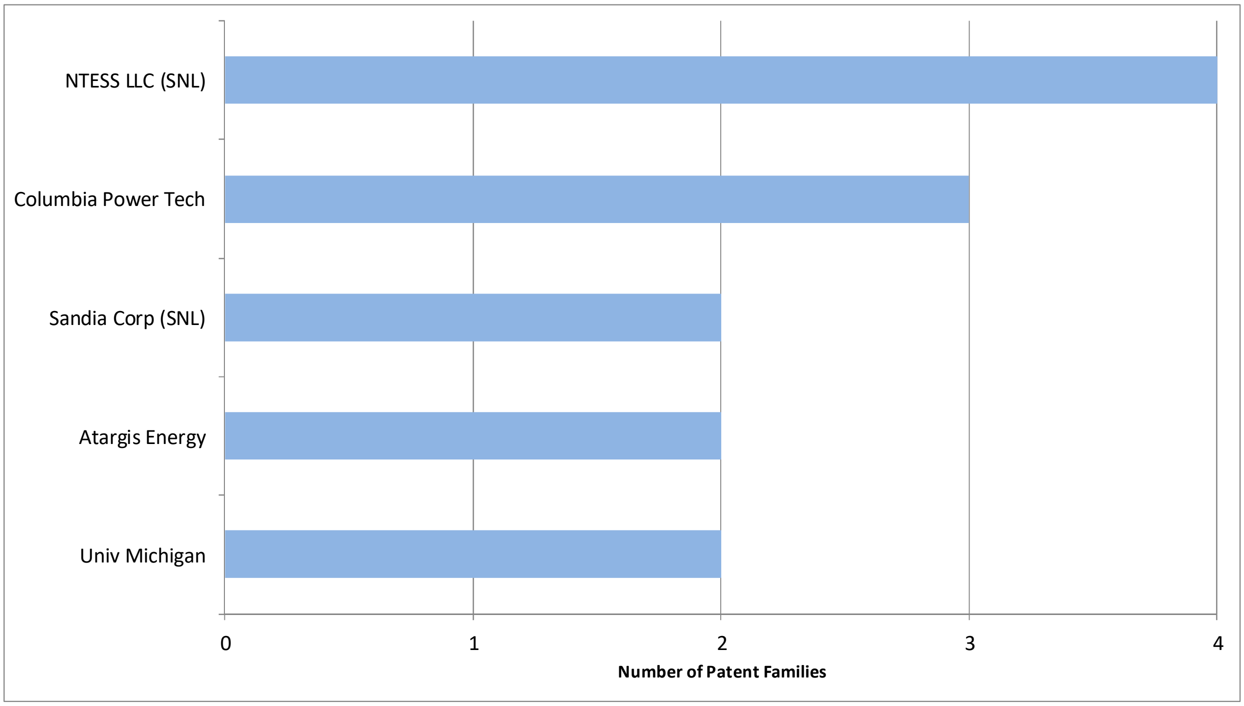
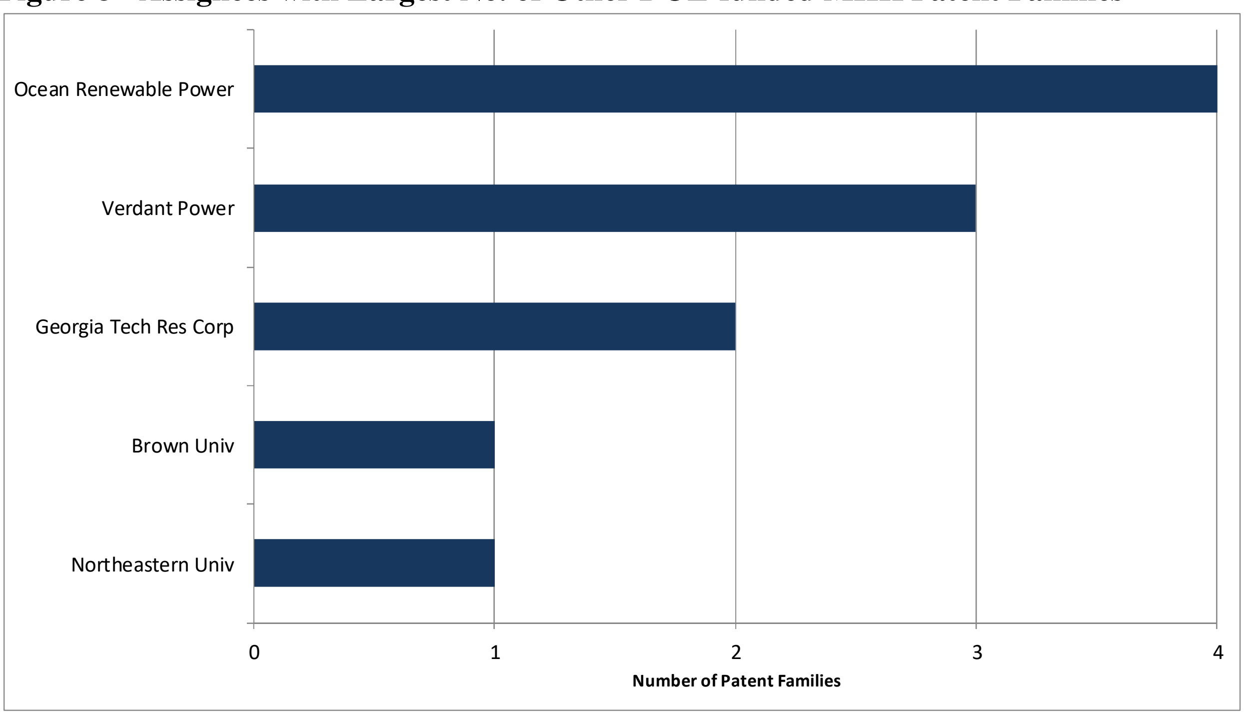


Figure 8 - Assignees with Largest No. of Other DOE-funded MHK Patent Families

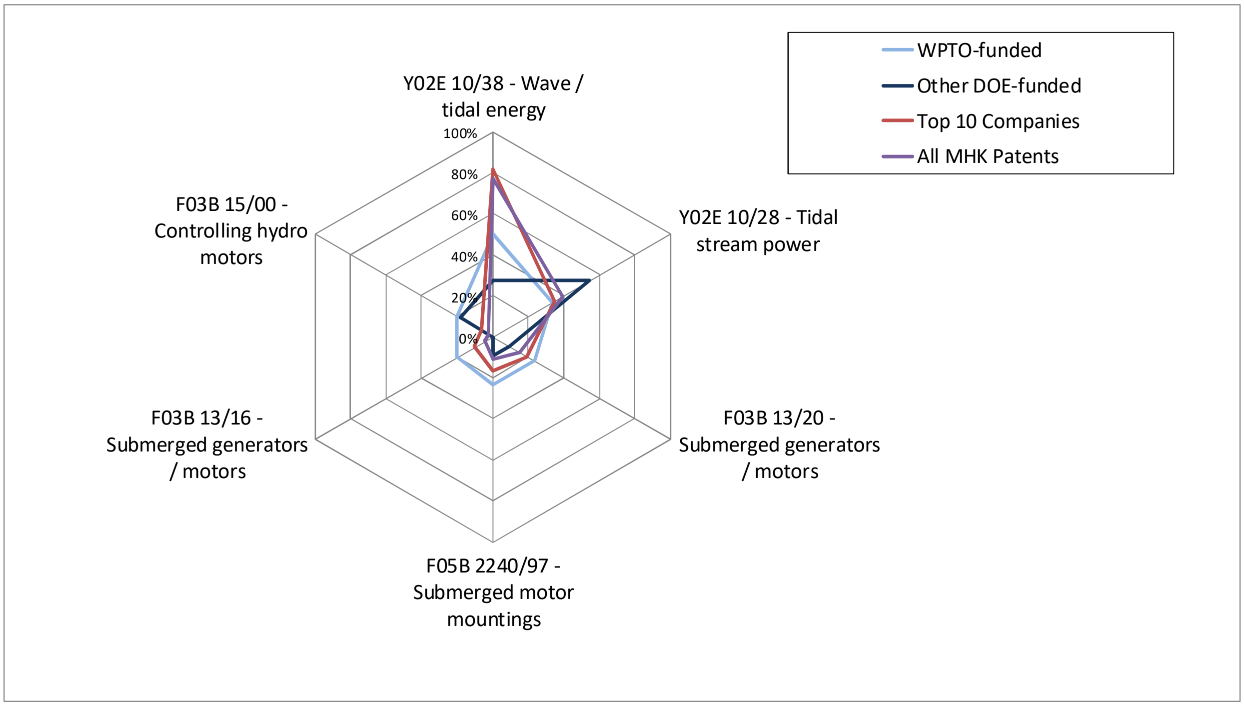


Distribution of MHK Patents across Patent Classifications

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

Figure 9 - Percentage of MHK U.S. Patents in Most Common Cooperative Patent Classifications (Among WPTO-Funded Patents)



This figure shows that WPTO-funded research includes relatively balanced coverage across the six CPCs (which is not particularly surprising, since the WPTO-funded patent portfolio forms the basis for the CPCs included in the chart). The most common CPC among WPTO-funded MHK patents is Y02E 10/38, which appears on 50% of these patents. This CPC is related to wave and tidal energy. The second most common CPC among WPTO-funded MHK patents is Y02E 10/28 (Tidal stream power), with one-third of the patents having this CPC attached. Other CPCs in Figure 9 focus on submerged motors and engines, plus mountings for these motors and methods

[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.

for controlling such motors. MHK patents in general, plus patents assigned to the leading companies, have an even greater focus than WPTO-funded patents on wave energy systems (CPC Y02E 10/38). Meanwhile, Other DOE-funded patents have a particular focus on tidal stream power (CPC Y02E 10/28).

Figure 10 is similar to Figure 9, except that it is from the perspective of the most common CPCs among all MHK patents. Hence, the purpose of this chart is to show the main research areas within MHK as a whole, and how these areas are represented in selected MHK portfolios (WPTO-funded; Other DOE-funded; leading MHK companies). Four of the six most common CPCs among all MHK patents in Figure 10 also appeared in Figure 9, and are concerned with wave and tidal energy, plus submerged motors and engines. The two new CPCs in Figure 10 (F03B 13/264 and F05B 2240/40) are also related to these technologies. This suggests that there is a high degree of overlap in terms of the technological concentrations of the various portfolios.

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

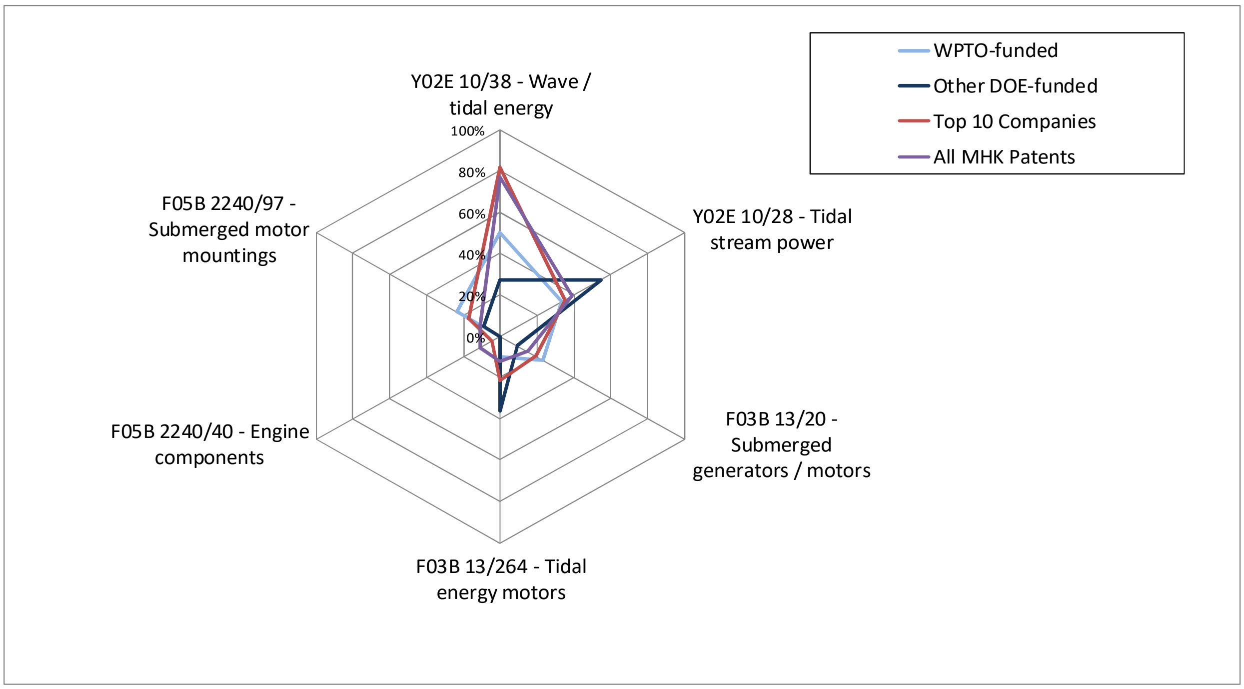
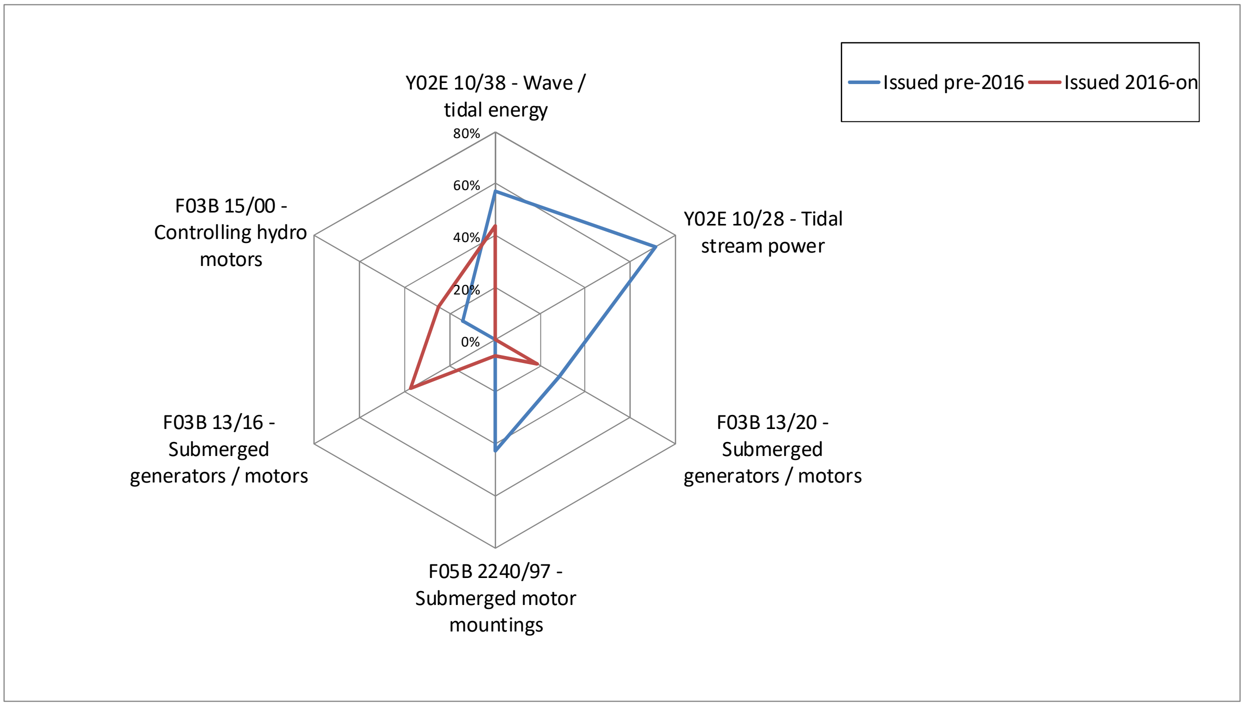


Figure 11 compares the CPC distribution of WPTO-funded MHK U.S. patents across two time periods – patents issued through 2015, and those issued from 2016 onwards (these dates were selected to divide the patents into two groups of approximately equal size). This figure reveals a shift in the CPC distribution across these two time periods. Perhaps the most notable difference is that, in the earlier period, over 70% of patents included a CPC related to tidal stream power (CPC Y02E 10/28). This CPC is absent from patents issued since 2016, suggesting that recent MHK research funded by WPTO has moved away from that technology area

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



Tracing Backwards from MHK Patents Owned by Leading Companies

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

Organizational Level Results

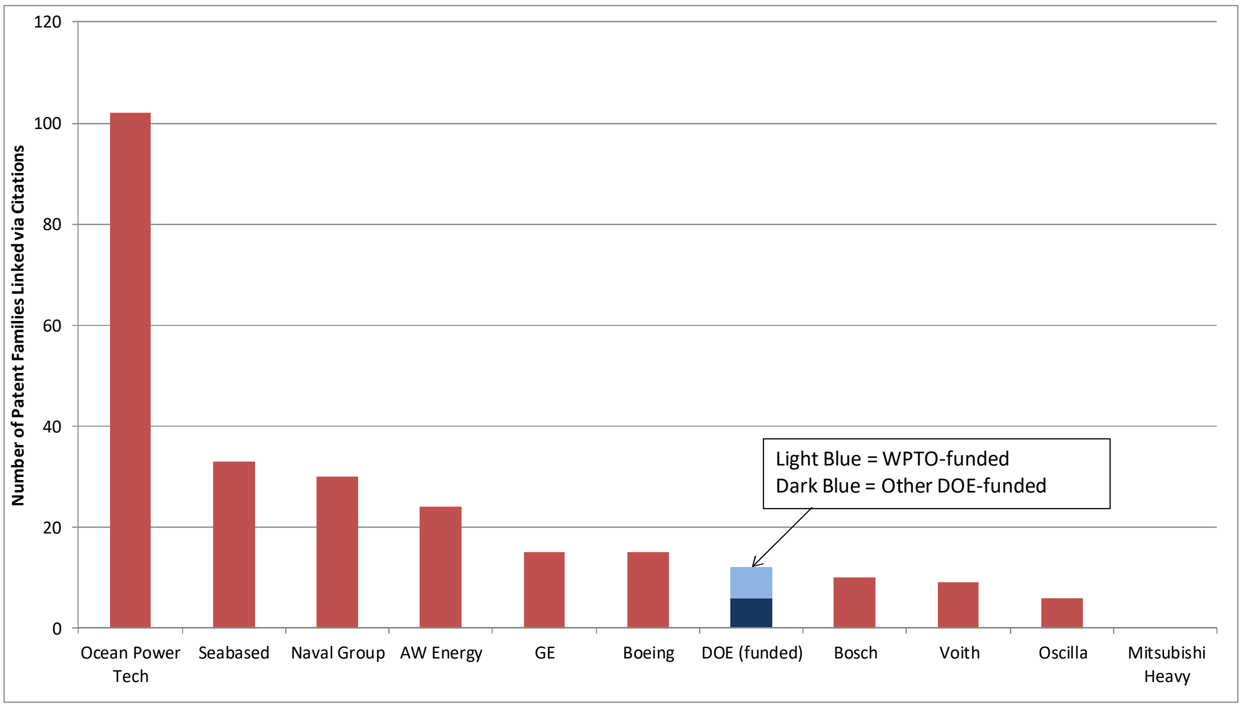
In the organizational level results, we first compare the influence of WPTO-funded and Other DOE-funded MHK research against the influence of leading MHK companies. We then look at which of these leading companies build particularly extensively on DOE-funded MHK research.

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

In total, twelve leading company MHK patent families (i.e. 3% of these 401 families) are linked via citations to earlier DOE-funded MHK patents, out of which six are linked to WPTO-funded MHK patents. This finding puts DOE-funded patents in seventh place in Figure 12. The figure is headed by Ocean Power Technologies, with 102 leading company patent families linked to its earlier patents, followed by Seabased (33 linked families) and Naval Group (30 linked families).

Figure 12 - Number of Leading Company MHK Patent Families Linked via Citations to Earlier MHK Patents from each Leading Company
e.g. 12 leading company families are linked to earlier WPTO/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 Ocean Power Technologies is at the head of this figure, since it has the most 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 via citations to patent families associated with each of the leading companies, plus DOE. This figure is again headed

[8] This figure compares the influence of patents *funded* by WPTO/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 a small amount of double-counting in Figure 12 and Figure 13, as one patent family assigned to Oscilla Power was funded by WPTO. Also, in Figures 12 and 14-15, leading company patent families linked to both WPTO-funded and Other DOE-funded patents are allocated to the WPTO-funded segment of the DOE column, in order to avoid double-counting these families.

by Ocean Power Technologies, Seabased and Naval Group, suggesting that these companies have the strongest citation links to subsequent leading company patents, even after accounting for the relative size of their patent portfolios. On average, DOE-funded MHK patent families (the majority of which are WPTO-funded) are each linked via citations to 0.34 patent families assigned to the leading companies. This puts DOE sixth in Figure 13. That said, it should be kept in mind that many of the DOE-funded (and particularly WPTO-funded) patent families are relatively recent, and so have not had much time to become linked via citations to subsequent generations of technology.

Figure 13 – Average Number of Leading Company MHK Patent Families Linked via Citations to MHK Families from Each Leading Company
e.g. on average, each DOE-funded family is linked to 0.34 subsequent leading company families

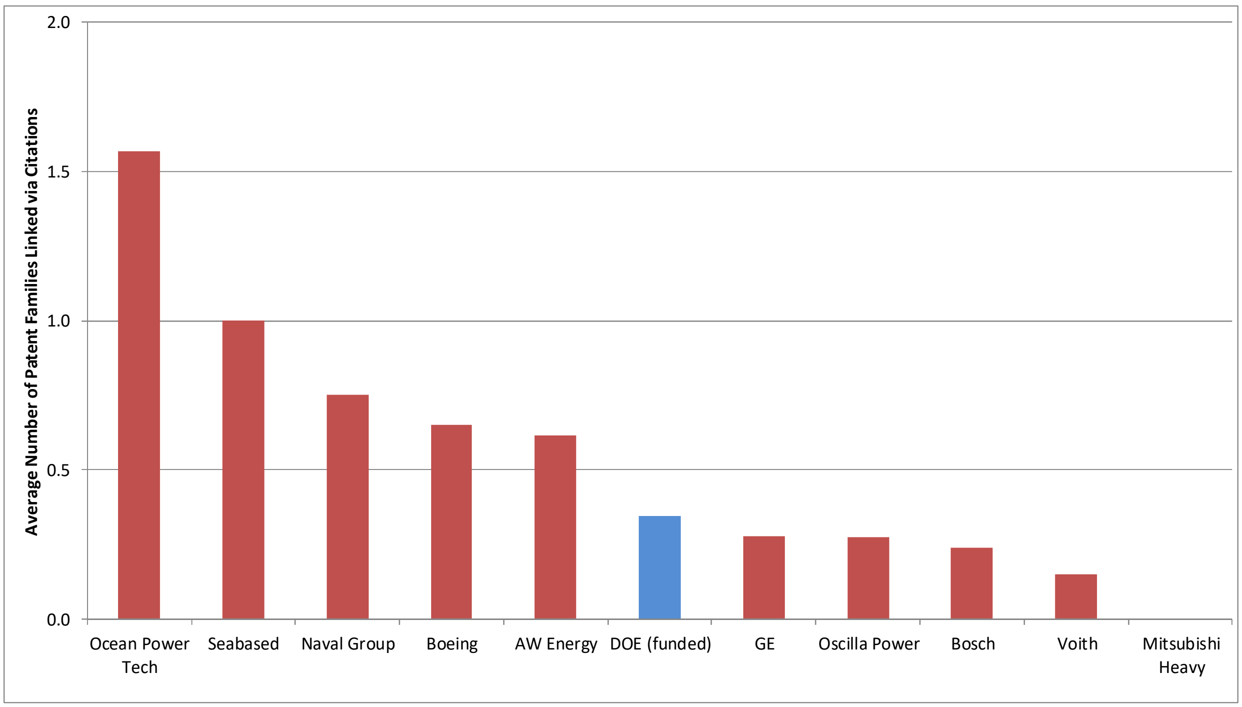


Figure 14 and Figure 15 examine which of the leading companies build most extensively on earlier DOE-funded patents. Figure 14 shows how many MHK patent families owned by each of the leading companies are linked via citations to at least one earlier DOE-funded MHK patent. Out of the ten leading MHK companies, six have at least one patent family linked via citations to earlier DOE-funded patents. Voith is at the head of this figure, with three patent families linked to Other DOE-funded MHK patents. Boeing (through its ownership of Liquid Robotics) and Oscilla both have two patent families linked to WPTO-funded patents, while General Electric has two patent families linked to Other DOE-funded patents.

Figure 15 shows the percentage of each leading company's MHK patent families that are linked via citations to earlier DOE-funded MHK 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. Boeing (Liquid Robotics) and Oscilla are at the head of Figure 15, with over 9% of their MHK patent families linked via citations to earlier WPTO-funded patents (although it should be noted that the numbers of patent families involved are very small – e.g.

two out of twenty-one families in the case of Boeing). Voith and Bosch both have 5% of their patent families linked to DOE-funded patents, but again the numbers of families are very small.

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

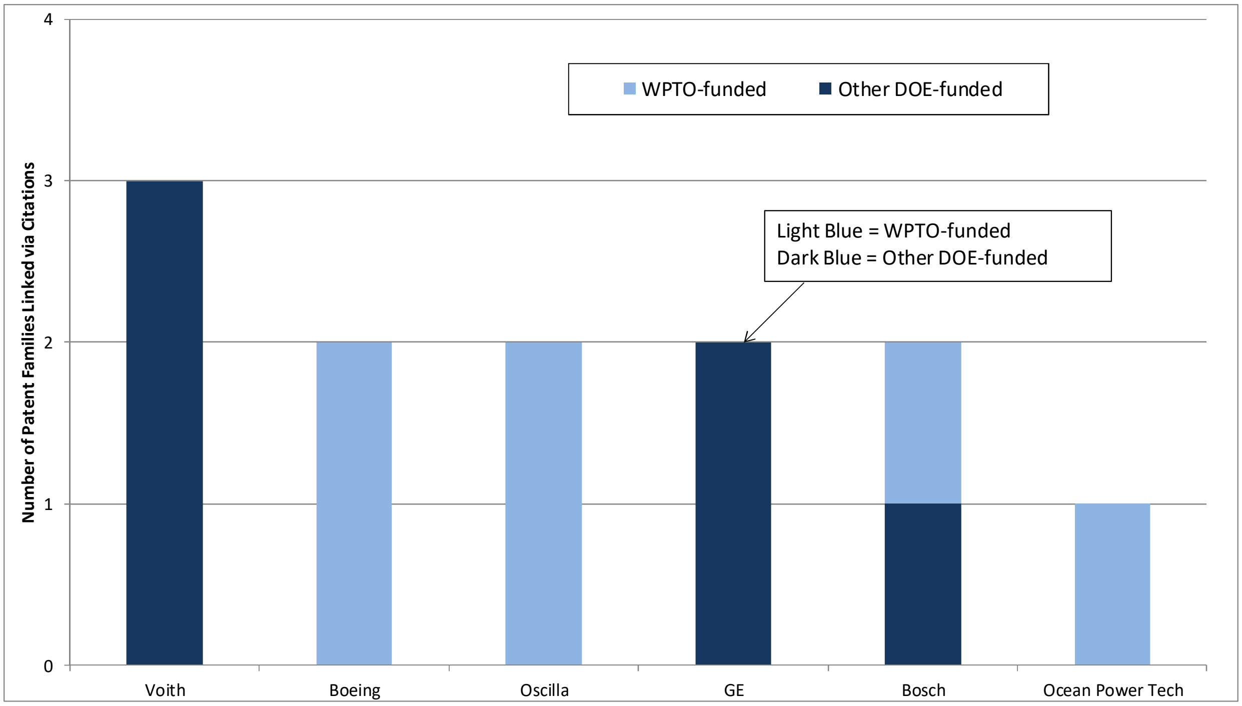
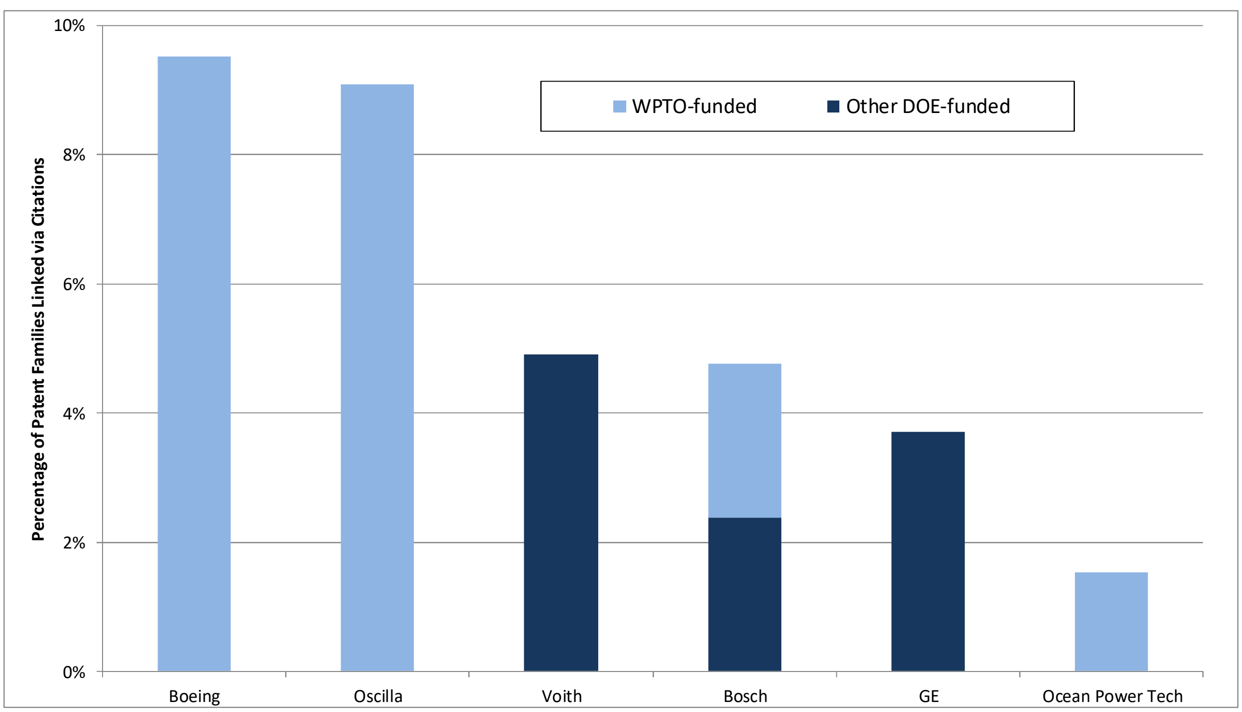


Figure 15 - Percentage of Leading MHK Company Patent Families Linked via Citations to Earlier WPTO/Other DOE-funded MHK Patents



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 MHK patent families (in particular WPTO-funded families) that have influenced subsequent patents owned by leading MHK companies. Looking in the opposite direction, it also identifies individual MHK patents owned by leading companies that are linked to earlier WPTO-funded research.

The organizational-level results revealed that there are six leading company patent families linked via citations to earlier WPTO-funded MHK patent families (see Figure 12). Examining the data at the individual patent level reveals that all six of these leading company families are linked to the same WPTO-funded patent family. This patent family (whose representative patent[9] is US #8,314,506) is shown in Table 5. It was filed in 2009 by Columbia Power Technologies and describes a wave energy converter designed to extract energy from both the horizontal (surge) and vertical (heave) components of ocean waves.

Table 5 – WPTO-Funded MHK Patent Families Linked via Citations to Most Subsequent Leading Company MHK Patent Families

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
42630308	8314506	2009	6	Columbia Power Technologies	Direct drive rotary wave energy conversion

Table 6 looks in the opposite direction to Table 5, and lists the six MHK patent families owned by leading companies that are linked to the WPTO-funded Columbia Power Technologies patent family in Table 5. Table 6 shows that this WPTO-funded patent family is linked via citations to subsequent wave energy converter patents assigned to Bosch, Ocean Power Technologies and Oscilla, plus Boeing (Liquid Robotics) patents outlining wave-powered water vehicles.

Table 6 - Leading Company MHK Patent Families Linked via Citations to Largest Number of WPTO-Funded MHK Patent Families

Patent Family #	Representative Patent #	Priority Year	# WPTO Fams	Assignee	Title
47424556	9353725	2014	1	Boeing (Liquid Robotics)	Watercraft and electricity generator system for harvesting electrical power from wave motion
46614579	9151267	2012	1	Boeing (Liquid Robotics)	Wave-powered devices configured for nesting
48576693	8884455	2012	1	Bosch	Wave energy converter, and associated operating method and control device
42933780	8456030	2010	1	Ocean Power Tech	Power take off apparatus for a WEC
49773787	9169823	2013	1	Oscilla Power	Magnetostrictive wave energy harvester with heave plate
55163980	9656728	2015	1	Oscilla Power	Method for deploying and recovering a wave energy converter

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

We also evaluated the subsequent impact of the six MHK patents owned by leading companies that have citation links back to WPTO-funded patents.[10] The idea is to highlight important technologies owned by leading companies that are linked to earlier MHK research funded by WPTO. Table 7 lists the three MHK patents owned by leading companies that have Citation Index values above one (i.e. they have been cited more frequently than expected), and are linked via citations to earlier WPTO-funded MHK patents. Two of the three patents (US #9,151,267 and US #9,353,725) are assigned to Boeing (Liquid Robotics) and describe wave-powered watercraft. Meanwhile, the third patent (US #9,169,823) is assigned to Oscilla, and outlines a heave plate for use in a wave energy system. The patents in Table 7 are all relatively recent, so the numbers of citations to them are still quite low. That said, early citation patterns suggest that these patents may contain interesting technological information.

Table 7 - Highly Cited Leading Company MHK Patents Linked via Citations to Earlier WPTO-funded MHK Patents

Patent	Issue Year	# Cites Received	Citation Index	Assignee	Title
9151267	2015	7	6.12	Boeing (Liquid Robotics)	Wave-powered devices configured for nesting
9353725	2016	3	3.51	Boeing (Liquid Robotics)	Watercraft and electricity generator system for harvesting electrical power from wave motion
9169823	2015	2	1.75	Oscilla Power	Magnetostrictive wave energy harvester with heave plate

While the patent-level results focus on WPTO-funded MHK patent families, we also identified Other DOE-funded MHK 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. Two of the four Other DOE-funded patent families in this table are assigned to Ocean Renewable Power Company. These families (representative patents US #7,902,687 and US #8,096,750) describe submersible turbines designed to generate energy from ocean and tidal currents. They are linked via citations to subsequent patent families assigned to Voith for a hydroelectric power plant, and families owned by General Electric (originally assigned to Blade Dynamics and Tidal Generation Limited) for turbine blades and underwater power cables. Table 8 also features an Other DOE-funded patent family assigned to Verdant Power (representative patent US #8,303,241) outlining an underwater turbine. It is linked via citations to two subsequent Voith

[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 F03B 13/20 (Submerged motors/engines) 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 a portfolio cited less frequently than expected. Note that the Citation Index is calculated for U.S. patents only, since citation rates differ across patent systems.

patent families for underwater power generation. The final patent family in Table 8 (representative patent US #5,074,710) is by far the oldest DOE-funded family in the analysis, having been filed in 1991. This family is assigned to Northeastern University, and describes water gates used to generate energy from tidal currents. It is linked via citations to a subsequent Bosch patent family outlining a crankshaft for use in wave energy motors.

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

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
39325123	7902687	2006	2	Ocean Renewable Power Co	Submersible turbine-generator unit for ocean and tidal currents
40623860	8303241	2007	2	Verdant Power	Turbine yaw control
42230237	8096750	2009	1	Ocean Renewable Power Co	High efficiency turbine and method of generating power
24800254	5074710	1991	1	Northeastern Univ	Water gate array for current flow or tidal movement pneumatic harnessing system

Overall, the backward tracing element of the analysis shows that WPTO-funded and Other DOE-funded MHK patents are linked to subsequent innovations associated with a number of the leading companies, notably Voith, Boeing and General Electric – with citations links to the latter two companies resulting from their acquisition of small wave power companies. That said, many of the DOE-funded MHK patents (and particularly WPTO-funded patents) are relatively recent, and so have not had a long period to establish links to subsequent generations of technology associated with the leading MHK companies.

Tracing Forwards from DOE-funded MHK Patents

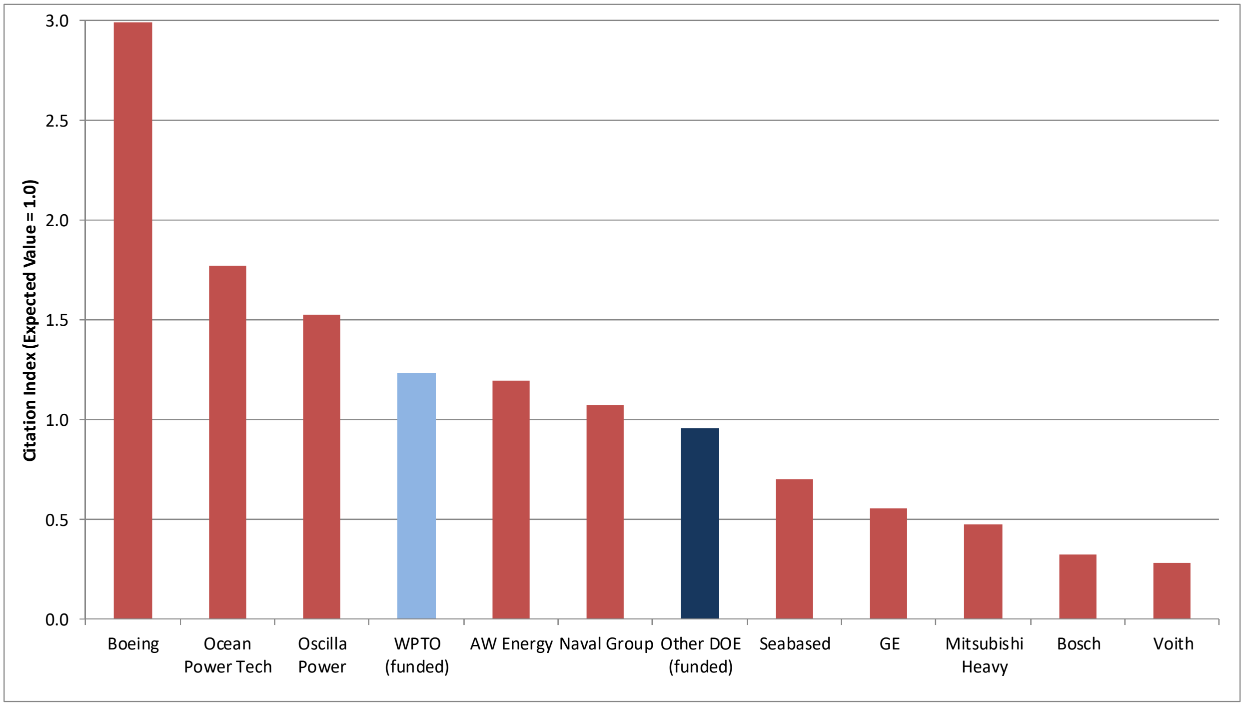
The previous section of the report examined the influence of DOE-funded MHK research upon technological developments associated with leading MHK companies. That analysis was based on tracing backwards from the patents of leading companies to previous generations of research. This section reports the results of an analysis tracing in the opposite direction – starting with WPTO-funded (and Other DOE-funded) MHK 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 MHK companies), this section of the report examines on the broader influence of WPTO-funded (and Other DOE-funded) MHK research, both within and beyond the MHK industry. Also, in order to avoid repeating earlier results, the forward tracing concentrates primarily on patents that are linked to DOE-funded MHK research, but are not owned by the leading MHK companies.

Organizational Level Results

We first generated Citation Index values for the portfolios of WPTO-funded and Other DOE-funded MHK patents. We then compared these Citation Indexes against those of the ten leading MHK companies. The results are shown in Figure 16. This figure reveals that WPTO-funded MHK patents have an average Citation Index of 1.24, showing they have been cited 24% more frequently than expected, given their age and technology. This puts WPTO-funded MHK patents in fourth place in Figure 16. The Citation Index for Other DOE-funded MHK patents is lower at

0.96, but still shows that these patents have been cited about as frequently as expected. Figure 16 is headed by Boeing, with a Citation Index of 2.99 (i.e. almost three times as many citations as expected), followed by Ocean Power Technologies (1.77) and Oscilla Power (1.53).

Figure 16 - Citation Index for Leading Companies' MHK Patents, plus WPTO-funded and Other DOE-funded MHK Patents



The Citation Index measures the overall influence of the DOE-funded MHK 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 MHK patent families.[11] These CPCs reflect the influence of DOE-funded research across technologies. Figure 17 lists the CPCs with the largest number of patent families linked via citations to WPTO-funded MHK patents. The CPCs are shown in two different colors – i.e. those related to MHK technology (dark green) and those beyond MHK technology (light green). The former represent the influence of WPTO-funded patents on MHK technology itself, while the latter represent spillovers of the influence of WPTO-funded MHK research into other technology areas.

Eight of the thirteen CPCs in Figure 17 are related to MHK, the most prominent being Y02E 10/38 (Wave/tidal energy) and Y02E 10/28 (Tidal stream power). Meanwhile, the non-MHK CPCs are all concerned with wind and airborne power generation, suggesting that WPTO-funded MHK research has influenced subsequent developments in 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 MHK patent families.

Figure 17 - Number of Patent Families Linked via Citations to Earlier WPTO-Funded MHK Patents by CPC (Dark Green = MHK-related; Light Green = Other)

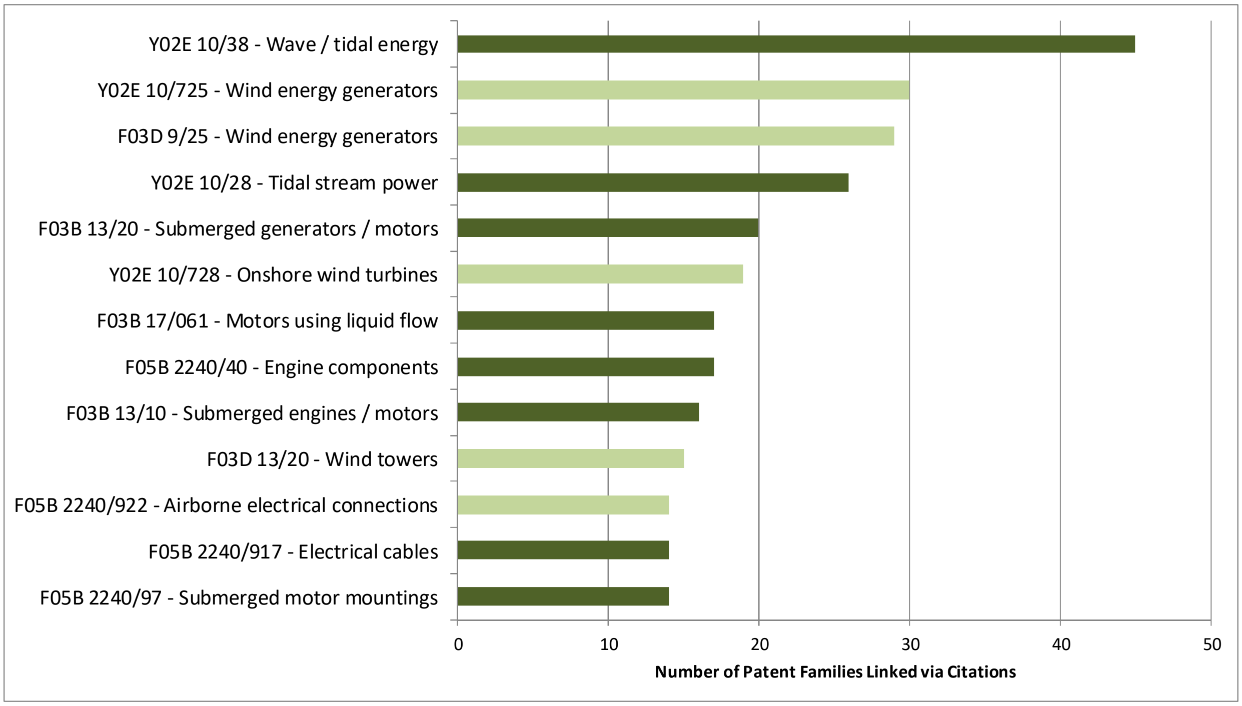


Figure 18 - Number of Patent Families Linked via Citations to Earlier Other DOE-Funded MHK Patents by CPC (Dark Green = MHK-related; Light Green = Other)

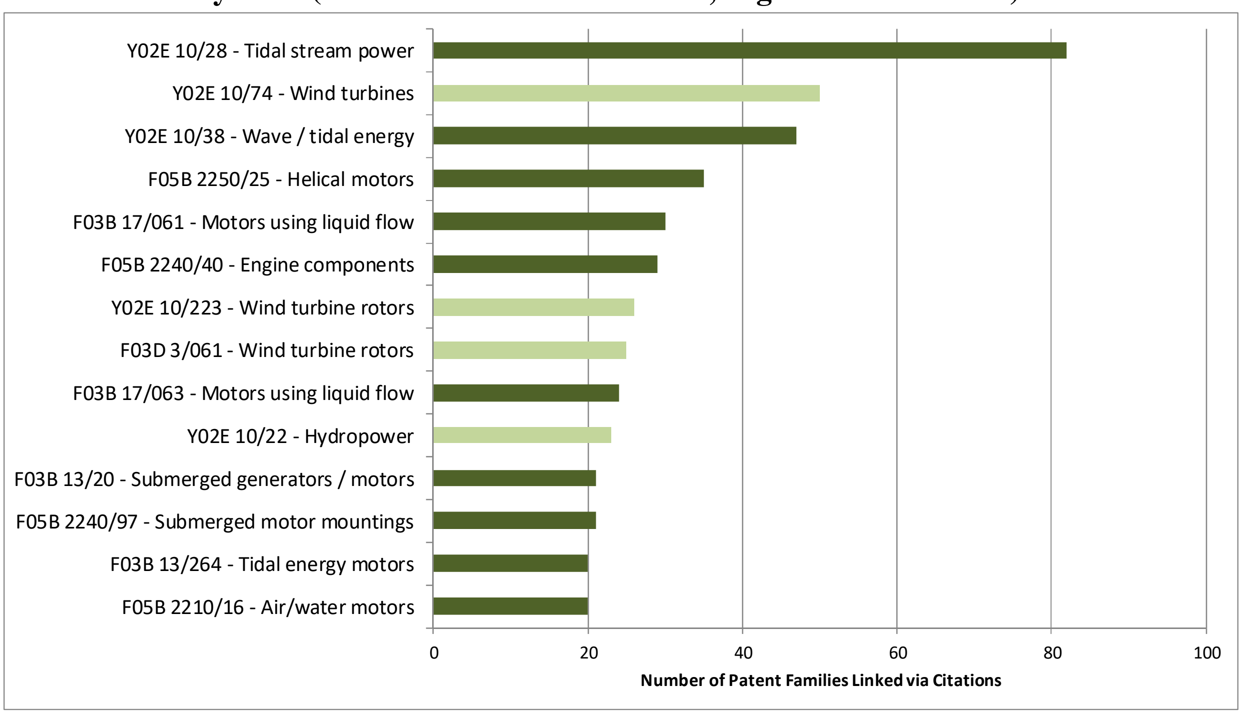


Figure 18 is similar to Figure 17, but is based on patent families linked to Other DOE-funded MHK patents, rather than WPTO-funded MHK patents. Again, the CPCs are shown in two colors depending on whether or not they are related to MHK technology. Ten of the fourteen CPCs in this figure are MHK-related, headed by CPCs covering tidal stream power (Y02E 10/28) and wave/tidal energy (Y02E 10/38). Moving beyond MHK, CPCs related to wind energy are prominent, as they were in Figure 17. Also, there is a CPC in Figure 18 (Y02E 10/22) connected to hydropower technology.

The organizations with the largest number of patent families linked via citations to earlier WPTO-funded MHK patents are shown in Figure 19. To avoid repeating the results from earlier, this figure excludes the ten leading MHK companies used in the backward tracing element of the analysis. Also, note that Figure 19 includes all patent families assigned to these organizations, not just their patent families describing MHK technology. Murtech Incorporated (a military and government contractor) is at the head of Figure 19, with ten patent families linked via citations to earlier WPTO-funded MHK patents. These Murtech patent families describe pumps for use in wave energy converters, plus the use of such converters in systems for producing potable water from bodies of salt water. Boulder Wind Power (a company founded by the ex-head of NREL's Wind Technology Center) is in second place in Figure 19, with eight patent families for wind turbine components and systems linked via citations to earlier WPTO-funded MHK patents. Meanwhile, the company in third place in Figure 19, Altaeros Energies, has four patent families outlining aerostats (moored balloons) for energy generation that are linked via citations to earlier WPTO-funded MHK patents. These are examples of the influence of these WPTO-funded patents extending into other technologies, as highlighted above in Figure 17.

Figure 19 - Organizations with Largest Number of Patent Families Linked via Citations to WPTO-funded MHK Patents (excluding leading MHK companies)

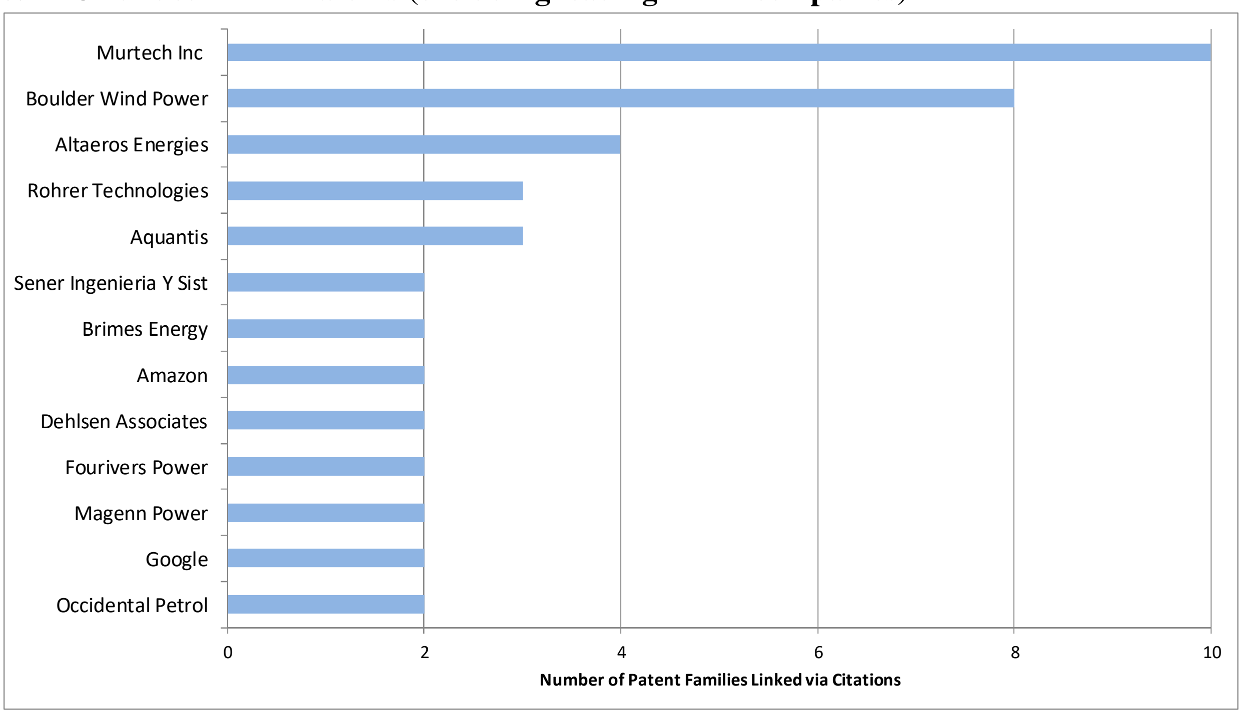
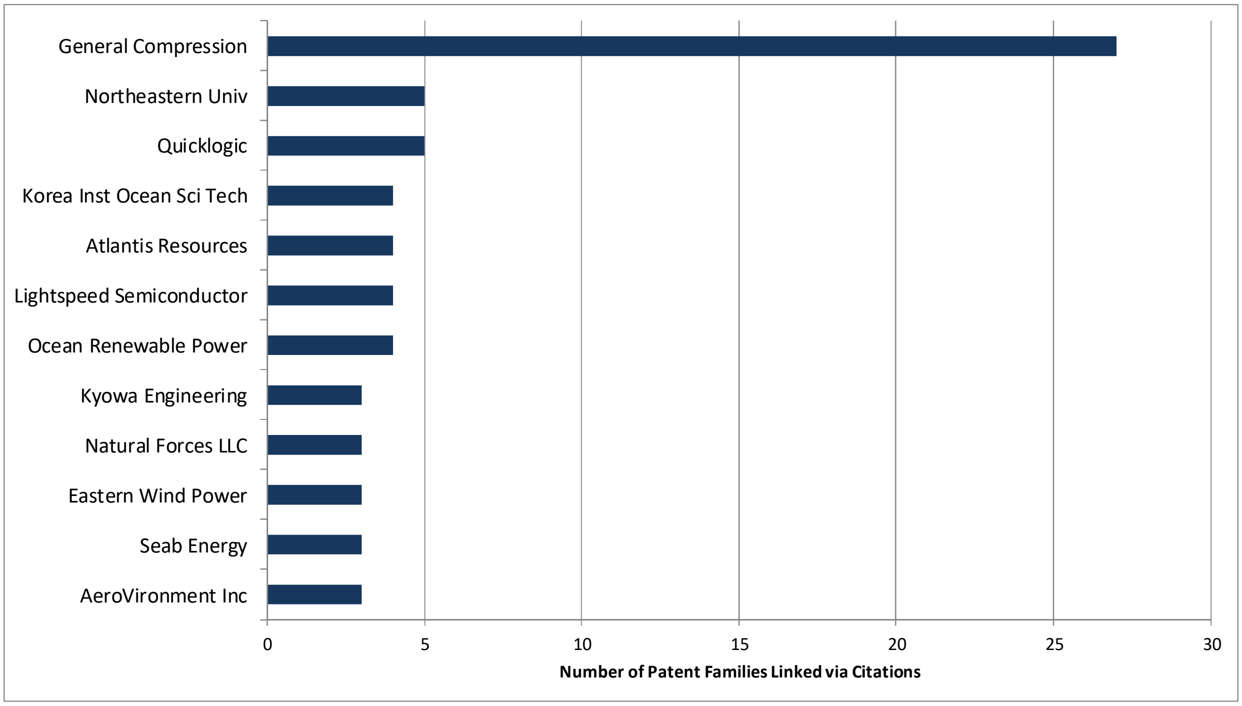


Figure 20 shows the organizations with the largest number of patent families linked to earlier Other DOE-funded MHK patents. This figure is headed by General Compression with 27 patent families describing compressed gas energy storage. These patent families are all linked via citations to the early (1991) Northeastern University patent family describing wave energy generation using water gates. Northeastern itself is in second place in Figure 20, with five later wave energy patent families linked via citations to the same initial Other DOE-funded family. The remaining organizations in Figure 20 are primarily renewable energy companies, although there are a small number of families owned by the semiconductor companies Quicklogic and Lightspeed.

Figure 20 - Organizations with Largest Number of Patent Families Linked via Citations to Other DOE-funded MHK Patents (excluding leading MHK companies)



Patent Level Results

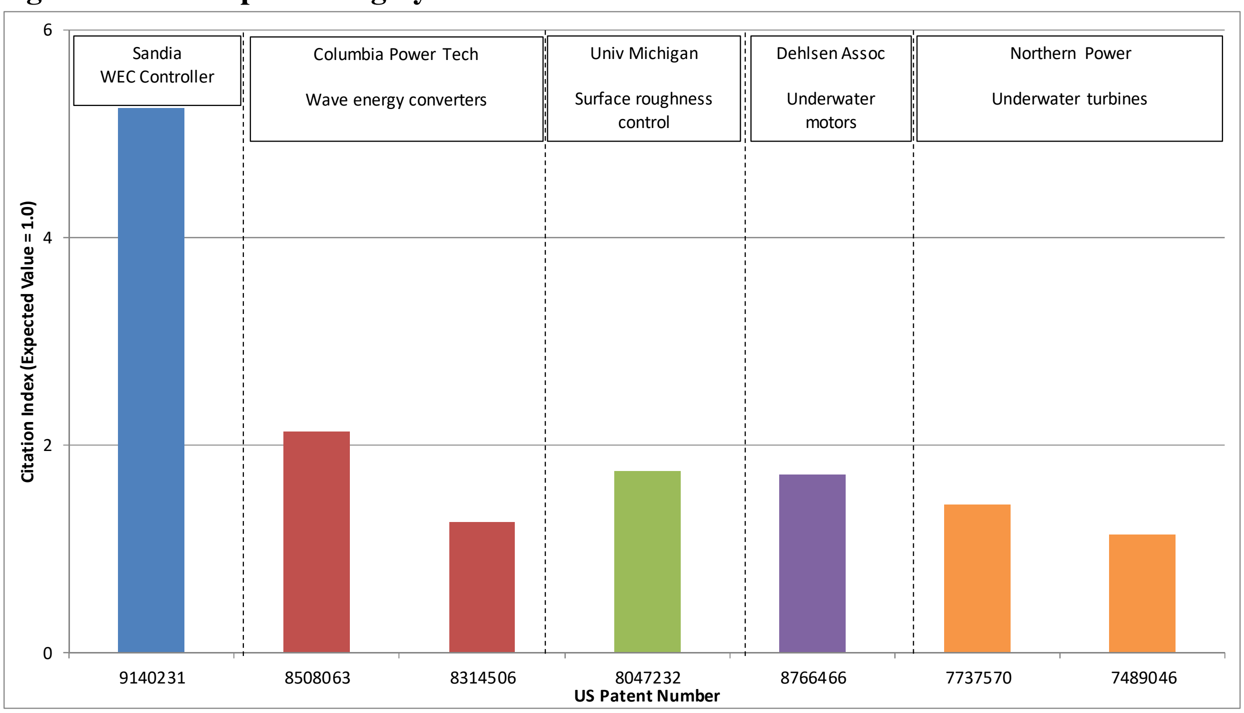
This section of the report drills down to identify individual DOE-funded (and particularly WPTO-funded) MHK patents whose influence on subsequent technological developments has been particularly strong. It also highlights patents that have extensive citation links to earlier WPTO-funded MHK research.

The simplest way of identifying high-impact WPTO-funded MHK patents is via overall Citation Indexes. The WPTO-funded patents with the highest Citation Index values are shown in Table 9, with selected patents also presented in Figure 21. The patents in this table are a mix of older patents that have been cited by numerous subsequent patents, and more recent patents that have attracted more citations than expected (although the citation counts associated with these patents is still quite low). 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 WPTO-Funded MHK Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
9140231	2015	6	5.24	Sandia Corp (SNL)	Controller for a wave energy converter
8508063	2013	7	2.13	Columbia Power Tech	Direct drive rotary wave energy conversion
8047232	2011	8	1.74	Univ Michigan	Enhancement of vortex induced forces and motion through surface roughness control
8766466	2014	5	1.71	Dehlsen Assoc (Aquantis)	Submerged electricity generation plane with marine current-driven rotors
7737570	2010	15	1.42	Northern Power Systems	Water turbine system and method of operation
8314506	2012	6	1.26	Columbia Power Tech	Direct drive rotary wave energy conversion
7489046	2009	16	1.13	Northern Power Systems	Water turbine system and method of operation

Figure 21 – Examples of Highly-Cited WPTO-funded MHK Patents



The patent at the head of Table 9 (US #7,004,724) is assigned to Sandia Corporation, through its management of Sandia National Laboratory. Since being issued in 2015, this patent has been cited as prior art by six subsequent patents (whereas the expected number of citations for a patent of its age and technology is just above one). It should be noted that some of these citations are from subsequent Sandia patents, although this patent has also started to attract citations from other organizations. Columbia Power Technologies has the patent in second place in Table 9, one of two patents it has in this table related to wave energy conversion systems. This patent (US #8,508,063) has been cited by seven subsequent patents since it was issued in 2013, more than twice as many citations as expected. In terms of raw citation counts, the two most highly-cited patents in Table 9 are slightly older Northern Power Systems patents describing submergible water turbine systems. These two patents (US #7,737,570 and US #7,489,046) have been cited by fifteen and sixteen subsequent patents respectively, slightly more citations than expected given their age and technology.

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

The patent family at the head of Table 10 contains the two Northern Power patents (US #7,489,046 and US #7,737,570) describing submergible water turbines patents highlighted above in Table 9. This patent family is linked via citations to 78 subsequent patent families, 23 of which are within MHK technology, with many of the remainder related to wind turbines and aerostats. The second patent family in Table 10 also contains patents highlighted above in Table 9 (US #8,314,506 and US #8,508,063). This patent family is assigned to Columbia Power Technologies, and describes a wave energy conversion system. It is linked to 38 subsequent patent families, 34 of which are within MHK technology. The third patent family in Table 10 (representative patent US #8,684,040) is assigned to the University of Michigan, and outlines a method for controlling the roughness of a surface to alter fluid flow around this surface. It is linked to eleven subsequent families, mostly related to marine risers and flotation devices.

Table 10 – WPTO-funded MHK Patent Families Linked via Citations to Largest Number of Subsequent MHK/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked MHK Fams	Assignee	Title
38821135	2006	7489046	78	23	Northern Power Systems	Water turbine system and method of operation
42630308	2009	8314506	38	34	Columbia Power Tech	Direct drive rotary wave energy conversion
40452299	2007	8684040	11	0	Univ Michigan	Reduction of vortex induced forces and motion through surface roughness control

The tables above identify WPTO-funded patent families linked particularly strongly to subsequent technological developments. Table 11 looks in the opposite direction, and identifies highly-cited patents linked to earlier WPTO-funded MHK patents. As such, these are examples where WPTO-funded MHK research has formed part of the foundation for subsequent high-impact technologies. This table focuses on patents not owned by the leading MHK companies, since those patents were covered in the backward tracing element of the analysis.

The two patents at the head of Table 11 are both assigned to Boulder Wind Power. The first of these patents (US #9,154,024) was granted in 2015 and 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 Boulder Wind Power patent in Table 11 (US #8,736,133) describes electrical motor windings, especially for wind turbines. This patent has been cited by 31 subsequent patents, twelve times as many citations as expected. The third patent in Table 11 (US #8,912,677), which has been cited by ten subsequent patents (five times as many as expected) is assigned to Dehlsen Associates and outlines a wave energy system. A number of the other patents in Table 11 are unassigned, meaning that their rights are owned by their inventors.

Table 11 - Highly Cited Patents (not from leading MHK companies) Linked via Citations to Earlier WPTO-funded MHK 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
8736133	2014	31	12.11	Boulder Wind Power	Methods and apparatus for overlapping windings
8912677	2014	10	5.46	Dehlsen Associates	Method and apparatus for converting ocean wave energy into electricity
8564151	2013	14	4.25	Unassigned	System and method for generating electricity
8178992	2012	16	3.27	Unassigned	Axial flux alternator with air gap maintaining arrangement
8443896	2013	13	2.77	Diamond Offshore Co	Riser floatation with anti-vibration strakes
7582981	2009	25	1.84	Unassigned	Airborne wind turbine electricity generating system
7859126	2010	17	1.68	Magenn Power	Systems and methods for tethered wind turbines
7851936	2010	13	1.23	Occidental Petrol Co	Water current power generation system

As with the backward tracing element of the analysis, the patent-level results from the forward tracing focus on WPTO-funded MHK patents. That said, within the forward tracing, we did also identify Other DOE-funded MHK patent families linked to the largest number of subsequent patent families within and beyond MHK technology. These Other DOE-funded MHK families are shown in Table 12.

Table 12 - Other DOE-funded MHK Patent Families Linked via Citations to Largest Number of Subsequent MHK/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked MHK Fams	Assignee	Title
24800254	1991	5074710	202	57	Northeastern Univ	Water gate array for current flow or tidal movement pneumatic harnessing system
39325123	2006	7902687	55	29	Ocean Renewable Power Co	Submersible turbine-generator unit for ocean and tidal currents
40640580	2007	7849596	13	1	Ocean Renewable Power Co	High efficiency turbine and method of making the same
42230237	2009	8096750	12	1	Ocean Renewable Power Co	High efficiency turbine and method of generating power

The patent family at the head of Table 12 (representative patent US #5,074,710) is assigned to Northeastern University and describes water gates for use in a wave energy system. This patent family was highlighted earlier in the report, and is by far the oldest DOE-funded family in the analysis, having been filed in 1991. It is linked via citations to 202 subsequent patent families, 57 of them within MHK technology, with the remainder covering a range of technologies, including energy storage, engine components and wind energy. The other three patent families in Table 13 are all assigned to Ocean Renewable Power. Out of these three families, one is linked particularly extensively via citations to subsequent patents. This family (representative patent US #7,902,687) describes a submergible turbine for use in wave energy generation. It is linked to 55 subsequent patent families, 29 of which are within MHK, with many of the others related to hydropower technology.

Overall, the forward tracing element of the analysis shows that WPTO-funded and Other DOE-funded MHK research has had a notable influence on subsequent technologies. This influence can be seen most extensively within MHK, but can also be traced in other technologies, notably wind energy and hydropower.

5.0 Conclusions

This report describes the results of an analysis tracing links between MHK research funded by DOE (WPTO plus Other DOE) and subsequent developments both within and beyond MHK 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 WPTO-funded (and Other DOE-funded) research forms a foundation for innovations associated with the leading MHK companies. The purpose of the forward tracing is to examine the influence of WPTO-funded (and Other DOE-funded) MHK patents upon subsequent developments, both within and outside MHK technology.

The backward tracing element of the analysis shows that WPTO-funded and Other DOE-funded MHK patents are linked to subsequent innovations associated with a number of the leading companies. Meanwhile, the forward tracing element of the analysis shows that WPTO-funded and Other DOE-funded MHK research has had a notable influence on subsequent technologies. This influence can be seen most extensively within MHK, but can also be traced in other technologies, notably wind energy and hydropower.

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

Appendix A. WPTO-funded MHK Patents used in the Analysis

Patent #	Application Year	Issue / Publication Year	Assignee	Title
WO2008147545	2008	2008	UNIVERSITY OF MICHIGAN	ENHANCEMENT OF VORTEX INDUCED FORCES AND MOTION THROUGHT SURFACE ROUGHNESS CONTROL
7489046	2006	2009	NORTHERN POWER SYSTEMS INC	WATER TURBINE SYSTEM AND METHOD OF OPERATION
WO2009035481	2008	2009	UNIVERSITY OF MICHIGAN	REDUCTION OF VORTEX INDUCED FORCES AND MOTION THROUGH SURFACE ROUGHNESS CONTROL
7737570	2009	2010	NORTHERN POWER SYSTEMS INC	WATER TURBINE SYSTEM AND METHOD OF OPERATION
EP2162347	2008	2010	UNIVERSITY OF MICHIGAN	ENHANCEMENT OF VORTEX INDUCED FORCES AND MOTION THROUGH SURFACE ROUGHNESS CONTROL
WO2010096195	2010	2010	COLUMBIA POWER TECHNOLOGIES INC	DIRECT DRIVE ROTARY WAVE ENERGY CONVERSION
7939957	2010	2011	NORTHERN POWER SYSTEMS INC	WATER TURBINE SYSTEM AND METHOD OF OPERATION
8047232	2008	2011	UNIVERSITY OF MICHIGAN	ENHANCEMENT OF VORTEX INDUCED FORCES AND MOTION THROUGH SURFACE ROUGHNESS CONTROL
EP2399023	2010	2011	COLUMBIA POWER TECHNOLOGIES INC	DIRECT DRIVE ROTARY WAVE ENERGY CONVERSION
8314506	2010	2012	COLUMBIA POWER TECHNOLOGIES INC	DIRECT DRIVE ROTARY WAVE ENERGY CONVERSION
WO2012112892	2012	2012	CONCEPTS ETI INC	TURBOMACHINERY HAVING SELF-ARTICULATING BLADES, SHUTTER VALVE, PARTIAL-ADMISSION SHUTTERS, AND/OR VARIABLE-PITCH INLET NOZZLES
WO2012138725	2012	2012	COLUMBIA POWER TECHNOLOGIES INC	A MECHANICAL ASSEMBLY FOR MAINTAINING AN AIR GAP BETWEEN A STATOR AND ROTOR IN AN ELECTRO-MECHANICAL ENERGY

				CONVERTER
8508063	2012	2013	COLUMBIA POWER TECHNOLOGIES INC	DIRECT DRIVE ROTARY WAVE ENERGY CONVERSION
WO2013066897	2012	2013	AQUANTIS INC	MULTI-MEGAWATT OCEAN CURRENT ENERGY EXTRACTION DEVICE
WO2013177491	2013	2013	UNIVERSITY OF MASSACHUSETTS	SYSTEMS AND METHODS FOR WAVE ENERGY CONVERSION
8659179	2013	2014	COLUMBIA POWER TECHNOLOGIES INC	DIRECT DRIVE ROTARY WAVE ENERGY CONVERSION
8684040	2008	2014	UNIVERSITY OF MICHIGAN	REDUCTION OF VORTEX INDUCED FORCES AND MOTION THROUGH SURFACE ROUGHNESS CONTROL
8766466	2012	2014	AQUANTIS INC	SUBMERGED ELECTRICITY GENERATION PLANE WITH MARINE CURRENT-DRIVEN ROTORS
EP2695282	2012	2014	COLUMBIA POWER TECHNOLOGIES INC	A MECHANICAL ASSEMBLY FOR MAINTAINING AN AIR GAP BETWEEN A STATOR AND ROTOR IN AN ELECTRO-MECHANICAL ENERGY CONVERTER
WO2014014599	2013	2014	US SYNTHETIC CORP	BEARING ASSEMBLIES, APPARATUSES, AND MOTOR ASSEMBLIES USING THE SAME
WO2014026019	2013	2014	ATARGIS ENERGY CORP	CLUSTERING OF CYCLOIDAL WAVE ENERGY CONVERTERS
WO2014026027	2013	2014	ATARGIS ENERGY CORP	OCEAN FLOOR MOUNTING OF WAVE ENERGY CONVERTERS
WO2014052953	2013	2014	COLUMBIA POWER TECHNOLOGIES INC	METHOD AND SYSTEM FOR WAVE ENERGY CONVERSION
8937395	2012	2015	ATARGIS ENERGY CORP	OCEAN FLOOR MOUNTING OF WAVE ENERGY CONVERTERS
8974184	2012	2015	CONCEPTS ETI INC	TURBOMACHINERY HAVING SELF-ARTICULATING BLADES, SHUTTER VALVE, PARTIAL-ADMISSION SHUTTERS, AND/OR VARIABLE PITCH INLET NOZZLES
9080548	2014	2015	AQUANTIS INC	METHOD OF CONTROLLING DEPTH OF A BUOYANT

				SUBMERSIBLE APPARATUS IN A FLUID FLOW
9140231	2013	2015	SANDIA CORP	CONTROLLER FOR A WAVE ENERGY CONVERTER
9222512	2012	2015	US SYNTHETIC CORP	BEARING ASSEMBLIES, APPARATUSES, AND MOTOR ASSEMBLIES USING THE SAME
EP2901008	2013	2015	COLUMBIA POWER TECHNOLOGIES INC	METHOD AND SYSTEM FOR WAVE ENERGY CONVERSION
9297351	2012	2016	ATARGIS ENERGY CORP	CLUSTERING OF CYCLOIDAL WAVE ENERGY CONVERTERS
9484779	2012	2016	COLUMBIA POWER TECHNOLOGIES INC	MECHANICAL ASSEMBLY FOR MAINTAINING AN AIR GAP BETWEEN A STATOR AND ROTOR IN AN ELECTRO-MECHANICAL ENERGY CONVERTER
WO2016014947	2015	2016	OSCILLA POWER INC	METHOD FOR DEPLOYING AND RECOVERING A WAVE ENERGY CONVERTER
9580608	2014	2017	SANDIA CORP	SWITCHABLE ANTIFOULING COATINGS AND USES THEREOF
9581128	2013	2017	UNIVERSITY OF MASSACHUSETTS	SYSTEMS AND METHODS FOR WAVE ENERGY CONVERSION
9587620	2014	2017	COLUMBIA POWER TECHNOLOGIES INC	METHOD AND SYSTEM FOR WAVE ENERGY CONVERSION
9656728	2015	2017	OSCILLA POWER INC	METHOD FOR DEPLOYING AND RECOVERING A WAVE ENERGY CONVERTER
9674406	2015	2017	UNIVERSITY OF WASHINGTON	USING DYNAMIC MODE DECOMPOSITION FOR REAL-TIME BACKGROUND/FOREGROUND SEPARATION IN VIDEO
EP3141741	2010	2017	COLUMBIA POWER TECHNOLOGIES INC	DIRECT DRIVE ROTARY WAVE ENERGY CONVERSION
WO2017062654	2016	2017	TEXAS A&M UNIVERSITY	METHOD AND APPARATUS FOR COMPACT AXIAL FLUX MAGNETICALLY GEARED MACHINES
WO2017205502	2017	2017	ABB SCHWEIZ AG	ELECTRO-DYNAMIC MACHINE, SYSTEM AND METHOD
9985483	2016	2018	ABB SCHWEIZ AG	ELECTRO-DYNAMIC MACHINE, SYSTEM AND

				METHOD
10066595	2016	2018	ALLIANCE FOR SUSTAINABLE ENERGY LLC	WAVE ENERGY CONVERSION INCORPORATING ACTUATED GEOMETRY
10067112	2015	2018	BATTELLE MEMORIAL INSTITUTE	AUTONOMOUS SENSOR FISH TO SUPPORT ADVANCED HYDROPOWER DEVELOPMENT
10197040	2017	2019	NTESS LLC	OPTIMAL CONTROL OF WAVE ENERGY CONVERTERS
10344736	2017	2019	NTESS LLC	PSEUDO-SPECTRAL METHOD TO CONTROL THREE DEGREE-OF-FREEDOM WAVE ENERGY CONVERTERS
10415537	2017	2019	NTESS LLC	MODEL PREDICTIVE CONTROL OF PARAMETRIC EXCITED PITCH-SURGE MODES IN WAVE ENERGY CONVERTERS
10423126	2017	2019	NTESS LLC	MULTI-RESONANT FEEDBACK CONTROL OF A SINGLE DEGREE-OF-FREEDOM WAVE ENERGY CONVERTER
10435568	2017	2019	SANDIA CORP	SWITCHABLE ANTIFOULING COATINGS AND USES THEREOF
10476349	2016	2019	TEXAS A&M UNIVERSITY	METHOD AND APPARATUS FOR COMPACT AXIAL FLUX MAGNETICALLY GEARED MACHINES

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

Patent #	Application Year	Issue / Publication Year	Assignee	Title
5074710	1991	1991	NORTHEASTERN UNIVERSITY	WATER GATE ARRAY FOR CURRENT FLOW OR TIDAL MOVEMENT PNEUMATIC HARNESSING SYSTEM
WO2008051455	2007	2008	OCEAN RENEWABLE POWER COMPANY LLC	SUBMERSIBLE TURBINE-GENERATOR UNIT FOR OCEAN AND TIDAL CURRENTS
EP2086830	2007	2009	OCEAN RENEWABLE POWER COMPANY LLC	SUBMERSIBLE TURBINE-GENERATOR UNIT FOR OCEAN AND TIDAL CURRENTS
WO2009064430	2008	2009	VERDANT POWER INC	IMPROVED TURBINE YAW CONTROL
WO2009067209	2008	2009	OCEAN RENEWABLE POWER COMPANY LLC	HIGH EFFICIENCY TURBINE AND METHOD OF MAKING THE SAME
WO2009067210	2008	2009	OCEAN RENEWABLE POWER COMPANY LLC	HIGH EFFICIENCY TURBINE AND METHOD OF GENERATING POWER
7789629	2006	2010	VERDANT POWER INC	NON-FOULING KINETIC HYDRO POWER SYSTEM AXIAL-FLOW BLADE TIP TREATMENT
7849596	2007	2010	OCEAN RENEWABLE POWER COMPANY LLC	HIGH EFFICIENCY TURBINE AND METHOD OF MAKING THE SAME
EP2222548	2008	2010	OCEAN RENEWABLE POWER COMPANY LLC	HIGH EFFICIENCY TURBINE AND METHOD OF GENERATING POWER
WO2010114794	2010	2010	OCEAN RENEWABLE POWER COMPANY LLC	HIGH EFFICIENCY TURBINE AND METHOD OF GENERATING POWER
7902687	2007	2011	OCEAN RENEWABLE POWER COMPANY LLC	SUBMERSIBLE TURBINE-GENERATOR UNIT FOR OCEAN AND TIDAL CURRENTS
8096750	2009	2012	OCEAN RENEWABLE POWER COMPANY LLC	HIGH EFFICIENCY TURBINE AND METHOD OF GENERATING POWER
8147201	2007	2012	VERDANT POWER INC	KINETIC HYDRO POWER TRIANGULAR BLADE HUB
8303241	2007	2012	VERDANT POWER INC	TURBINE YAW CONTROL
EP2414223	2010	2012	OCEAN RENEWABLE	HIGH EFFICIENCY TURBINE AND METHOD OF

			POWER COMPANY LLC	GENERATING POWER
8393853	2007	2013	OCEAN RENEWABLE POWER COMPANY LLC	HIGH EFFICIENCY TURBINE AND METHOD OF GENERATING POWER
WO2014113809	2014	2014	BROWN UNIVERSITY	KINETIC ENERGY HARVESTING USING CYBER-PHYSICAL SYSTEMS
9394875	2015	2016	GEORGIA TECH RESEARCH CORPORATION	SYSTEM FOR HARVESTING WATER WAVE ENERGY
EP2992205	2014	2016	BROWN UNIVERSITY	KINETIC ENERGY HARVESTING USING CYBER-PHYSICAL SYSTEMS
10087910	2014	2018	BROWN UNIVERSITY	KINETIC ENERGY HARVESTING USING CYBER-PHYSICAL SYSTEMS
10333430	2015	2019	GEORGIA TECH RESEARCH CORPORATION	ROBUST TRIBOELECTRIC NANOGENERATOR BASED ON ROLLING ELECTRIFICATION

An Analysis of the Influence of WPTO-funded MHK Patents

Report prepared by 1790 Analytics LLC

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