The Influence of Additive Manufacturing Patents Funded by the U.S. Department of Energy's Advanced Manufacturing Office and Other DOE Offices

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Executive Summary

This report describes the results of an analysis tracing the technological influence of additive manufacturing research funded by the U.S. Department of Energy (DOE)'s Advanced Manufacturing Office (AMO) and its precursor programs, as well as additive manufacturing research funded by other offices in DOE (Other 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 AMO-funded, and Other DOE-funded, additive manufacturing research has formed a foundation for innovations patented by leading organizations in this technology. Meanwhile, the primary purpose of the forward tracing is to examine the broader influence of AMO-funded and Other DOE-funded additive manufacturing research upon subsequent developments, both within and outside additive manufacturing technology.

The main finding of this report is:

- Additive manufacturing research funded by DOE has had a significant influence on subsequent developments, both within and beyond additive manufacturing technology. This influence can be seen on innovations associated with many of the leading additive manufacturing companies. It can also be traced in other technologies, including advanced materials, electronics and semiconductors, and medical devices. Much of DOE's influence can be attributed to Other DOE-funded patents. AMO is a relatively new source of funding in additive manufacturing, so AMO-funded patents have had little time to influence subsequent developments.

More detailed findings from this report include:

- In additive manufacturing technology, in the period 1976-2018, we identified a total of 24,511 patents (8,461 U.S. patents, 7,040 EPO patents and 9,010 WIPO patents). We grouped these patents into 17,237 patent families, where each family contains all patents resulting from the same initial application (named the 'priority application').

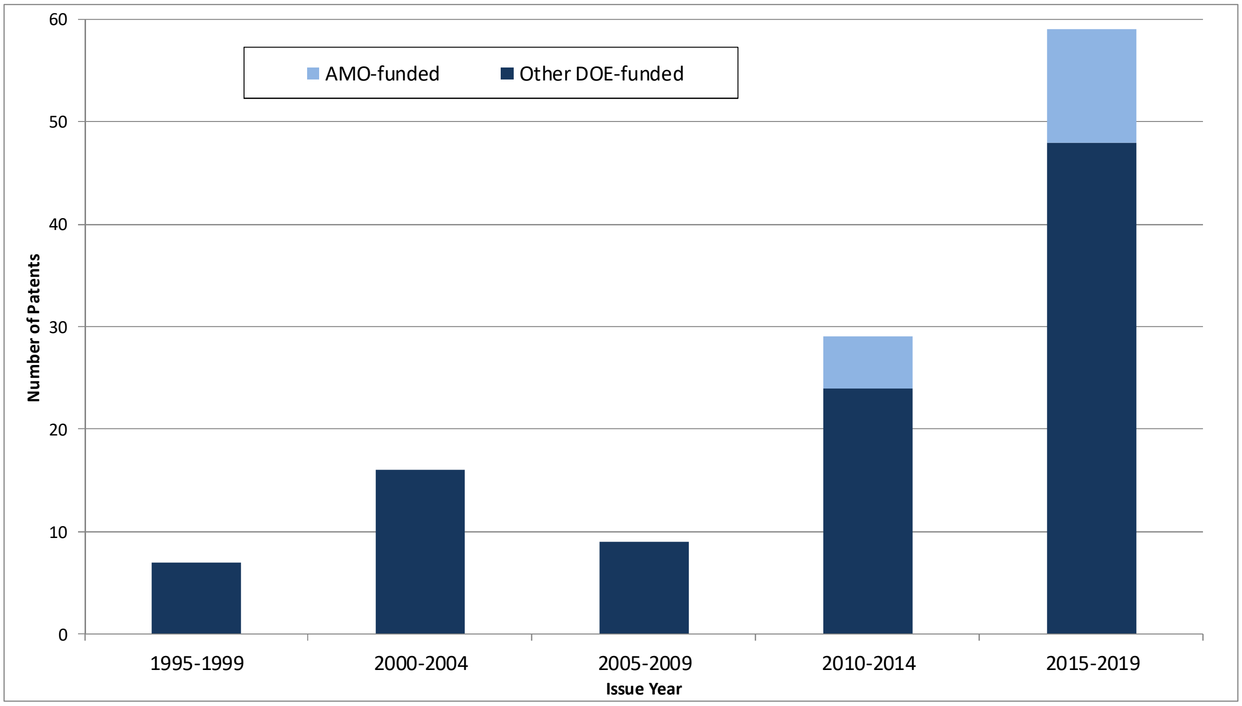
- 20 additive manufacturing patents are confirmed to be associated with AMO funding (16 U.S. patents, one EPO patent, and three WIPO patents). We grouped these AMO-funded additive manufacturing patents into 14 patent families.

- In addition, we identified a further 138 additive manufacturing patents (105 U.S. patents, 14 EPO patents and 19 WIPO patents) that are associated with DOE funding. These Other DOE-funded patents are grouped into 78 patent families.

- The total number of DOE-funded additive manufacturing patents (AMO-funded plus Other DOE-funded) is 158, corresponding to 92 patent families. This represents 0.5% of the total number of additive manufacturing patent families in the period 1976-2018.

- Figure E-1 shows the number of AMO-funded and Other DOE-funded additive manufacturing U.S. patents by issue year. This figure shows that DOE-funded additive manufacturing patenting is primarily focused in the most recent time periods in the analysis. The peak in patenting came in 2015-2019, even though data for this period are incomplete (see note below Figure E-1), with 59 U.S. patents granted in this period (11 of them AMO-funded).

Figure E-1 - Number of AMO/Other DOE-Funded Additive Manufacturing 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 AMO. No new patent search for 2019 was carried out.

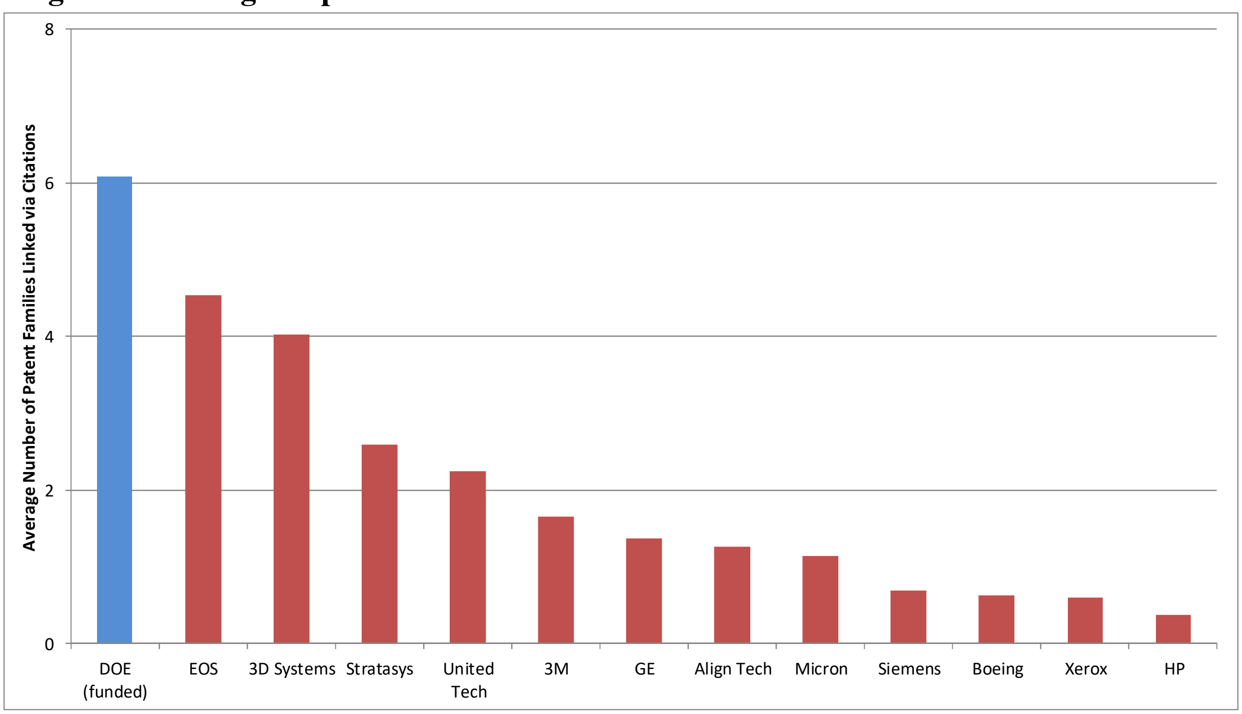
- The Other DOE-funded additive manufacturing patent portfolio is both much larger and more established than the AMO-funded portfolio, with the latter representing a growing, but still relatively small, percentage of the total number of DOE-funded patents and patent families. This contrast between the two portfolios is reflected in the findings outlined in this report.

- The twelve companies with the largest additive manufacturing patent portfolios are: Hewlett-Packard (764 patent families); General Electric (506); Stratasys (468); 3D Systems (438); United Technologies (386); Siemens (357); Micron (253); 3M (201); Align Technology (194); Xerox (184); Boeing (184) and EOS (181). In comparison, the portfolio of 92 DOE-funded additive manufacturing patent families (14 AMO-funded; 78 Other DOE funded) is much smaller than those of the leading companies. This difference in size is taken into account in evaluating the influence of the various portfolios.

- AMO-funded patents cover technologies including additive manufacturing apparatus, materials and processes, plus objects produced using additive manufacturing techniques. Other DOE-funded patents, leading company patents and additive manufacturing patents overall also have a notable presence in these technologies. This suggests that AMO-funded additive manufacturing research is aligned with research in this technology in general. That said, Other DOE-funded patents have a somewhat greater focus on objects produced using additive manufacturing, while the leading companies have more patents outlining additive manufacturing data management.

- On average, DOE-funded additive manufacturing patent families (most of which are Other DOE-funded) are each linked via citations to over six subsequent patent families assigned to the leading additive manufacturing companies (see Figure E-2). This puts DOE at the head of Figure E-2. It means that, on average, more additive manufacturing patent families owned by leading companies are linked via citations to each DOE-funded patent family than are linked to the patent families assigned to any other leading company. This suggests that, taking into account its relatively small size, the portfolio of DOE-funded additive manufacturing additive manufacturing patents has helped form an important part of the foundation for innovations associated with the leading companies.

Figure E-2 - Average No. of Leading Company Additive Manufacturing Patent Families Linked via Citations to Additive Manufacturing Families from Each Leading Company e.g. on average, each DOE-funded patent family is linked to six subsequent patent families assigned to leading companies



- Out of the leading companies, 36% of Micron's additive manufacturing patent families are linked via citations to earlier DOE-funded patents. Stratasys has 29% of its additive manufacturing patent families linked via citations to DOE, while General Electric has

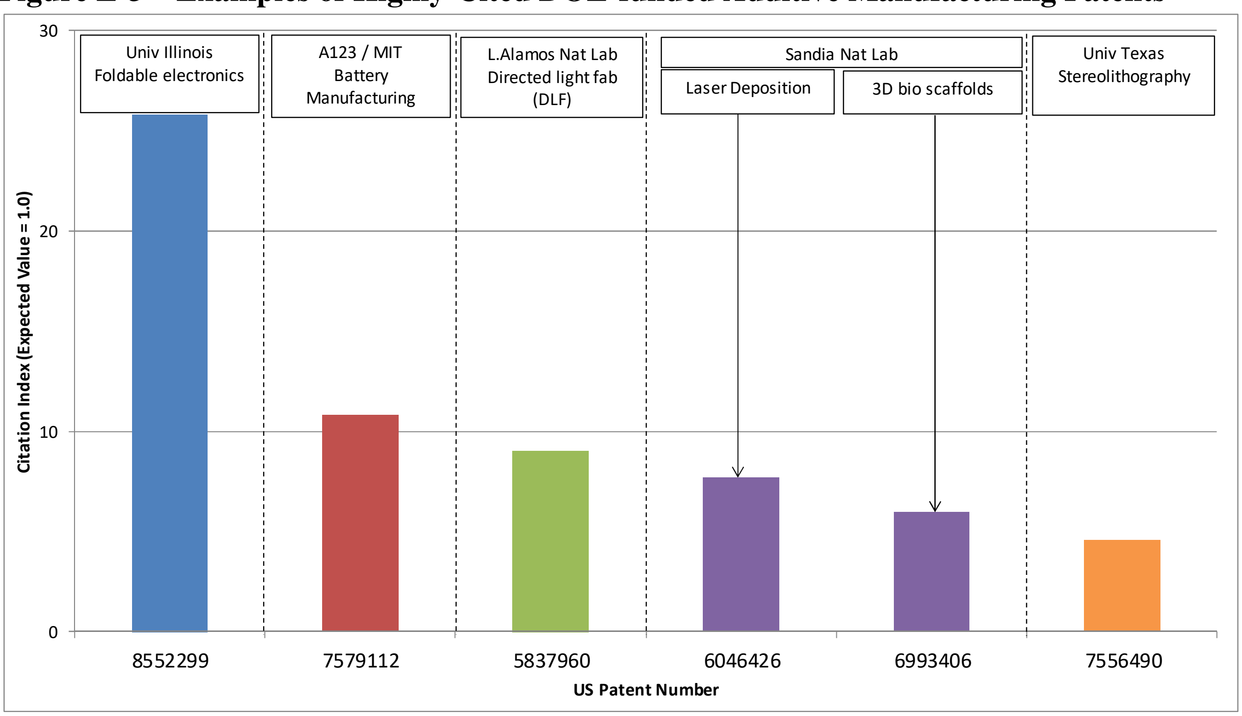
22%. These companies thus appear to build particularly extensively on earlier DOE-funded (and primarily Other DOE-funded) additive manufacturing research.

- Other DOE-funded additive manufacturing patents have an average Citation Index value of 2.99 (the Citation Index is a normalized citation metric with an expected value of 1.0; a value of 2.99 shows that, based on their age and technology, Other DOE-funded additive manufacturing patents have been cited as prior art almost three times as frequently as expected by subsequent patents). AMO-funded patents have a lower Citation Index of 0.79 (i.e. 21% fewer citations than expected). That said, many of the AMO-funded patents are very recent, and so have not had much time to be cited by subsequent patents.

- The influence of DOE-funded additive manufacturing patents can be seen both within additive manufacturing technology, and in other technologies such as electronics, semiconductors, advanced materials and medical devices.

- There are a number of individual high-impact DOE-funded additive manufacturing patents, examples of which are shown in Figure E-3 (these patents are all are Other DOE-funded). They include a University of Illinois patent describing foldable electronics; a patent for battery manufacturing assigned to A123 Systems and MIT; a Los Alamos National Laboratory patent outlining directed light fabrication; Sandia National Laboratory patents for laser deposition and 3D printing of bio-scaffolds; and a University of Texas patent related to stereolithography.

Figure E-3 – Examples of Highly-Cited DOE-funded Additive Manufacturing Patents



1.0 Introduction

This report focuses on additive manufacturing technology. Its objective is to trace the influence of additive manufacturing research funded by the Department of Energy (DOE) Advanced Manufacturing Office (AMO) – plus additive manufacturing research funded by DOE as a whole – on subsequent developments both within and outside additive manufacturing technology. The purpose of the report is to:

(i) Locate patents awarded for key AMO-funded (and other DOE-funded) innovations in additive manufacturing technology; and

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

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

[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 AMO-funded additive manufacturing patents and Other DOE-funded additive manufacturing patents. However, referring repeatedly to “AMO-funded/Other DOE-funded patents” or “AMO-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.

to demonstrate how the new invention is original over and above this prior art. Prior art references may include many different types of public documents. A large number of the references are to earlier patents, and these references form the basis for this study. Other references (not covered in this study) may be to scientific papers and other types of documents, such as technical reports, magazines and newspapers.

The responsibility for adding prior art references differs across patent systems. In the U.S. patent system, it is the duty of patent applicants to reference (or "cite") all prior art of which they are aware that may affect the patentability of their invention. Patent examiners may then reference additional prior art that limits the claims of the patent for which an application is being filed. In contrast to this, in patents filed at the European Patent Office (EPO) and World Intellectual Property Organization (WIPO), prior art references are added solely by the examiner, rather than by both the applicant and examiner. The number of prior art references on EPO and WIPO patents thus tends to be much lower than the number on U.S. patents.[3]

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

Patent citation analysis has also been used extensively to trace technological developments over time. For example, in the analysis presented in this report, we use citations from patents to earlier patents to trace the influence of DOE-funded additive manufacturing research. Specifically, we identify cases where patents cite DOE-funded additive manufacturing 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 additive manufacturing 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 additive manufacturing research. By determining how frequently DOE-funded additive manufacturing patents have been cited by subsequent patents, it is thus

[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.

possible to evaluate the extent to which DOE-funded research forms a foundation for various technologies both within and beyond additive manufacturing.

Forward and Backward Tracing

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

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

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

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

The idea behind adding the second generation of citations is that agencies such as DOE often support basic scientific research. It may take time, and numerous generations of research, for this basic research to be used in an applied technology, for example that described in a patent owned by a leading company. Introducing a second generation of citations provides greater access to these indirect links between basic research and applied technology. That said, one potential problem with adding generations of citations must be acknowledged. Specifically, if one uses enough generations of links, eventually almost every node in the network will be linked. This is a problem common to many networks, whether these networks consist of people, institutions, or scientific documents. 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 additive manufacturing patents, and also for the patents owned by leading additive manufacturing organizations. We also assembled families for all patents linked via citations to DOE-funded additive manufacturing 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

[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.

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.

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

3.0 Methodology

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

Identifying AMO-funded and Other DOE-funded Additive Manufacturing Patents

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

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

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

(iii) Categorizing these DOE-funded additive manufacturing patents according to whether or not they can be linked definitively to AMO 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 Additive Manufacturing Patents

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

Filter A
Cooperative Patent Classification
B33Y – Additive manufacturing
B29C 64 – Additive manufacturing using plastics
Y02P 10/29-295 – Additive manufacturing, including metals
Filter B
Title/Abstract
Additive(-)manufactur*
Additive(-)fabricat*
Free(-)form fabricat*
3(-)d(-)print*
Three(-)dimensional(-)print*

We manually checked this initial list of patents to determine which of them appear relevant to additive manufacturing, and then sent the resulting patent list to AMO for review. Following this review, and based on feedback from AMO, the initial list of additive manufacturing patents funded by DOE contained a total of 112 granted U.S. patents.

Defining AMO-funded vs. Other DOE-funded Additive Manufacturing 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 112 DOE-funded additive manufacturing patents in the initial list could be linked definitively to AMO 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 AMO technology managers to verify individual patents,
- (iv) Asking AMO 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 AMO, 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 AMO-funded/Other DOE-funded Additive Manufacturing Patents

Based on the process described above, we divided the initial list of 112 DOE-funded additive manufacturing U.S. patents into two categories – AMO-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 the final number of AMO-funded and Other DOE-funded additive manufacturing patents and patent families. This table shows that we identified a total of 14 AMO-funded additive manufacturing patent families, containing 16 U.S. patents, one EPO patent, and three WIPO patents (see Appendix A for patent list). We also identified 78 Other DOE-funded additive manufacturing patent families, containing 105 U.S. patents, 14 EPO patents, and 19 WIPO patents (see Appendix B for patent list). Note that the AMO-funded patents are all relatively recent, with the earliest being filed in 2007, while the Other DOE-funded portfolio is more established, with the earliest application filed in 1994.

Table 3 – Number of AMO-funded and Other DOE-funded Additive Manufacturing Patents and Patent Families

	# Patent Families	# U.S. Patents	# EPO Patents	# WIPO Patents
AMO-funded	14	16	1	3
Other DOE-funded	78	105	14	19
Total DOE-funded	92	121	15	22

Identifying Additive Manufacturing Patents Assigned to Leading Organizations

The backward tracing element of our analysis is designed to evaluate the influence of AMO-funded (and Other DOE-funded) research on additive manufacturing innovations produced by leading organizations in this technology. To identify such organizations, we first defined the universe of additive manufacturing patents in the period 1976-2018 using the patent filter detailed earlier in Table 2. Based on this filter, we identified a total of 8,461 U.S. patents, 7,040 EPO patents, and 9,010 WIPO patents. We grouped these patents into 17,237 patent families by matching priority documents. We then located the most prolific organizations in this additive manufacturing patent universe, based on number of patent families. The twelve organizations with the largest number of additive manufacturing patent families are shown in Table 4.[6]

[6] All twelve of these organizations are companies. For clarity, they are referred to in the results section of the report as the leading additive manufacturing 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

Table 4 – Top 12 Patenting Additive Manufacturing Companies

Company	# Additive Mfg Patent Families
Hewlett-Packard	764
General Electric	506
Stratasys	468
3D Systems	438
United Technologies	386
Siemens	357
Micron Technology	253
3M	201
Align Technology	194
Xerox	184
Boeing	184
EOS (Electro Optical Systems)	181

The number of patent families listed in Table 4 includes all variant names under which these companies have patents, taking into account all subsidiaries and acquisitions. The additive manufacturing patent families of the twelve 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 additive manufacturing technology. The patent sets for the forward tracing consisted of AMO-funded (and, separately, Other DOE-funded) additive manufacturing patent families. We then traced backward through two generations of citations from the leading organizations' additive manufacturing patents, and forward through two generations of citations from the AMO/Other DOE-funded additive manufacturing 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 AMO-funded and Other DOE-funded additive manufacturing research on subsequent developments both within and beyond additive manufacturing technology. The results are divided into three main sections. In the first section, we examine trends in additive manufacturing patenting over time, and assess the distribution of AMO-funded and Other DOE-funded patents across additive manufacturing technologies. The second section then reports the results of an analysis tracing backwards from additive manufacturing patents owned by the leading companies in this technology. The purpose of this analysis is to determine the extent to which additive manufacturing innovations developed by leading companies build upon earlier additive

be the leading patenting additive manufacturing companies, but this is a cumbersome description to use throughout the results section of the report.

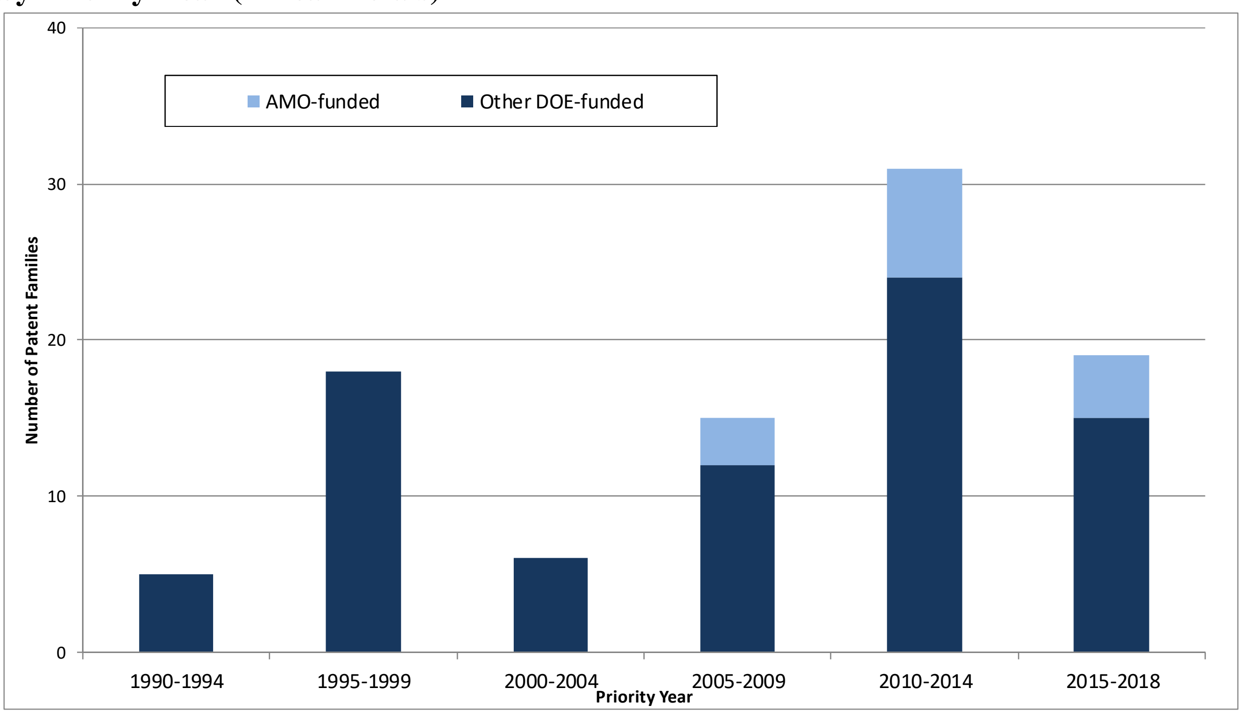
manufacturing research funded by AMO (plus additive manufacturing research funded by the remainder of DOE). In the third section, we report the results of an analysis tracing forwards from AMO-funded (and Other DOE-funded) additive manufacturing patents. The purpose of this analysis is to assess the broader influence of DOE-funded research upon subsequent developments within and beyond additive manufacturing.

Overall Trends in Additive Manufacturing Patenting

Trends in Additive Manufacturing Patenting over Time

Figure 1 shows the number of AMO-funded and Other DOE-funded additive manufacturing patent families by priority year – i.e. the year of the first application in each patent family. AMO-funded patent families are shown in light blue and Other DOE-funded families in dark blue. This figure reveals that the earliest DOE-funded additive manufacturing patent families were filed in 1990-1994, with five families filed in this period (all defined as Other DOE-funded). The number grew to 18 in 1995-1999, before falling back to six in 2000-2004. Again, all patent families from these time periods were Other DOE-funded. The number of DOE-funded patent families then increased to 15 in 2005-2009 (three AMO-funded) and 31 in 2010-2014 (seven AMO-funded). The number of patent families in 2015-2018 is lower at 19 (four AMO-funded), although data for this period are incomplete (see note below Figure 1). Overall, there are 14 AMO-funded and 78 Other DOE-funded additive manufacturing patent families. The portfolio of Other DOE-funded patents is thus much larger, and has a longer history, than the portfolio of AMO-funded patents.

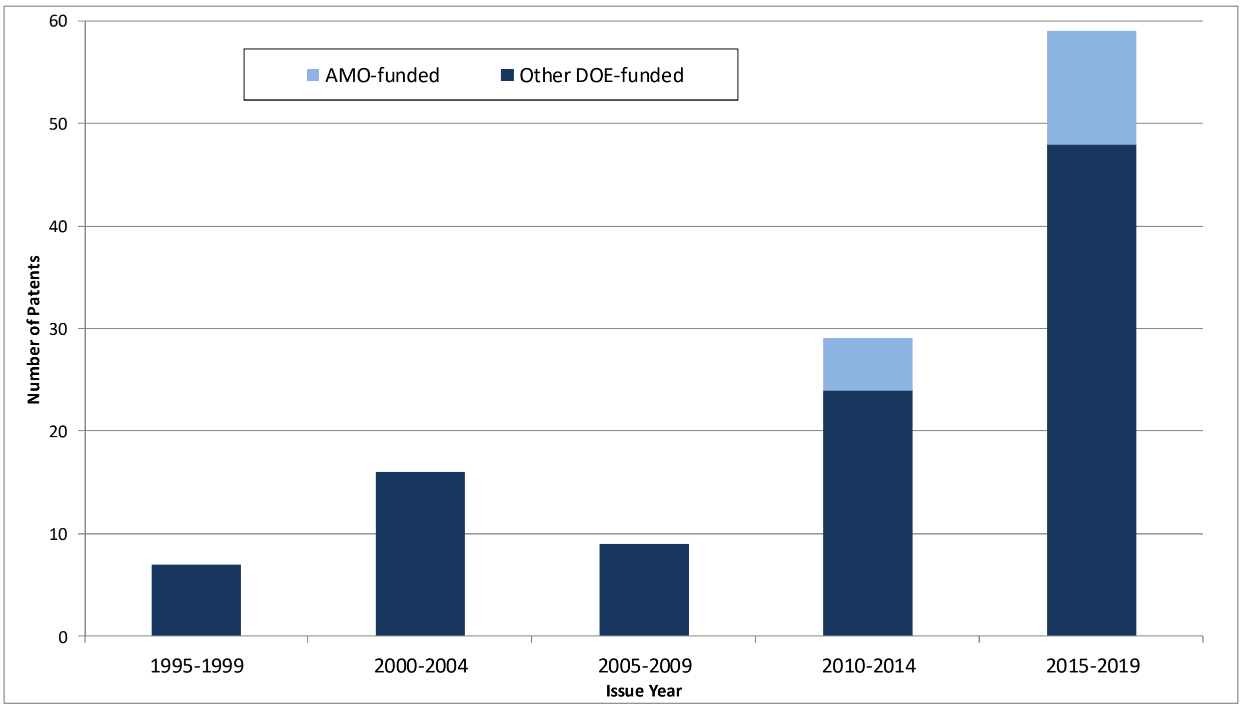
Figure 1 – Number of AMO/Other DOE-funded Additive Manufacturing Patent Families by Priority Year (5-Year Totals)



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 additive manufacturing patenting is primarily focused in the most recent time periods in the analysis, with Other DOE-funded patents representing the bulk of these patents. This pattern is also reflected in Figure 2, which shows the number of additive manufacturing granted U.S. patents funded by DOE in each time period. Here, the first seven DOE-funded patents were issued in 1995-1999, followed by an increase to 18 patents in 2000-2004, and then a decrease to nine patents in 2005-2009. All patents from these time periods are defined as Other DOE-funded. The number of DOE-funded patents then increased sharply, to 29 in 2010-2014, with five of these patents being AMO-funded. The number increased further to 59 in 2015-2019 (11 of them AMO-funded), even though data for this time period are incomplete (see note below Figure 2).

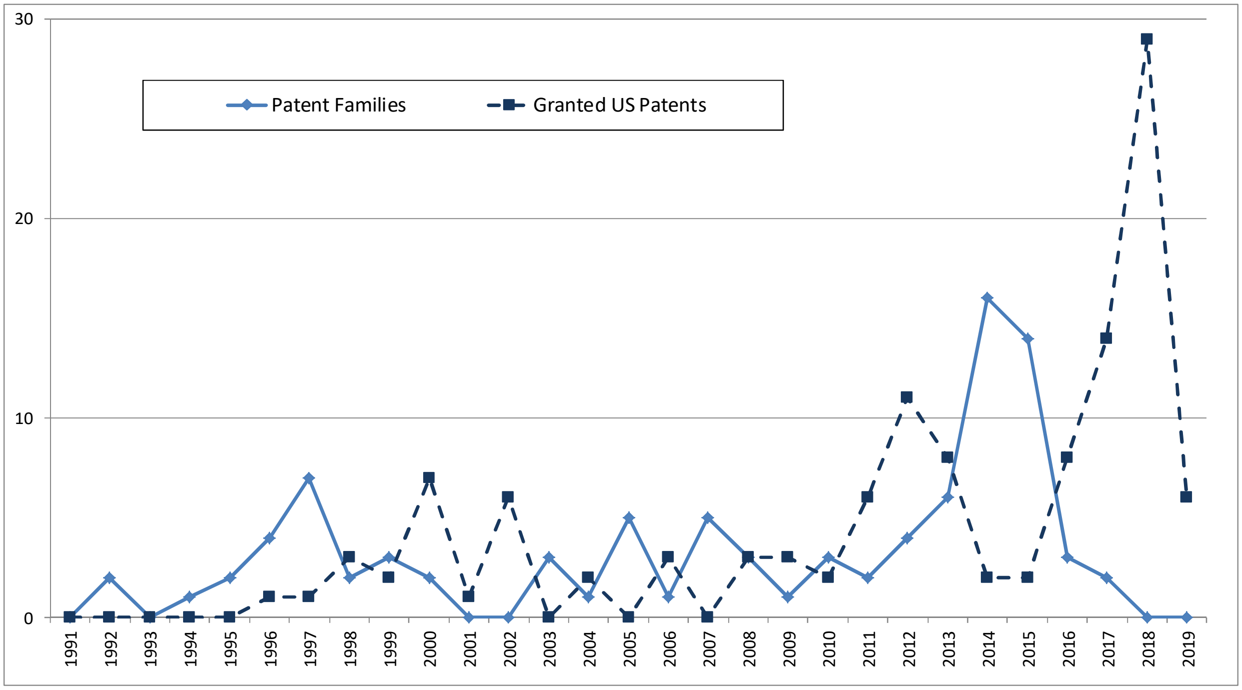
Figure 2 – Number of AMO/Other DOE-Funded Additive Manufacturing U.S. Patents by Issue Year (5-Yr Totals)



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 AMO. No new patent search for 2019 was carried out.

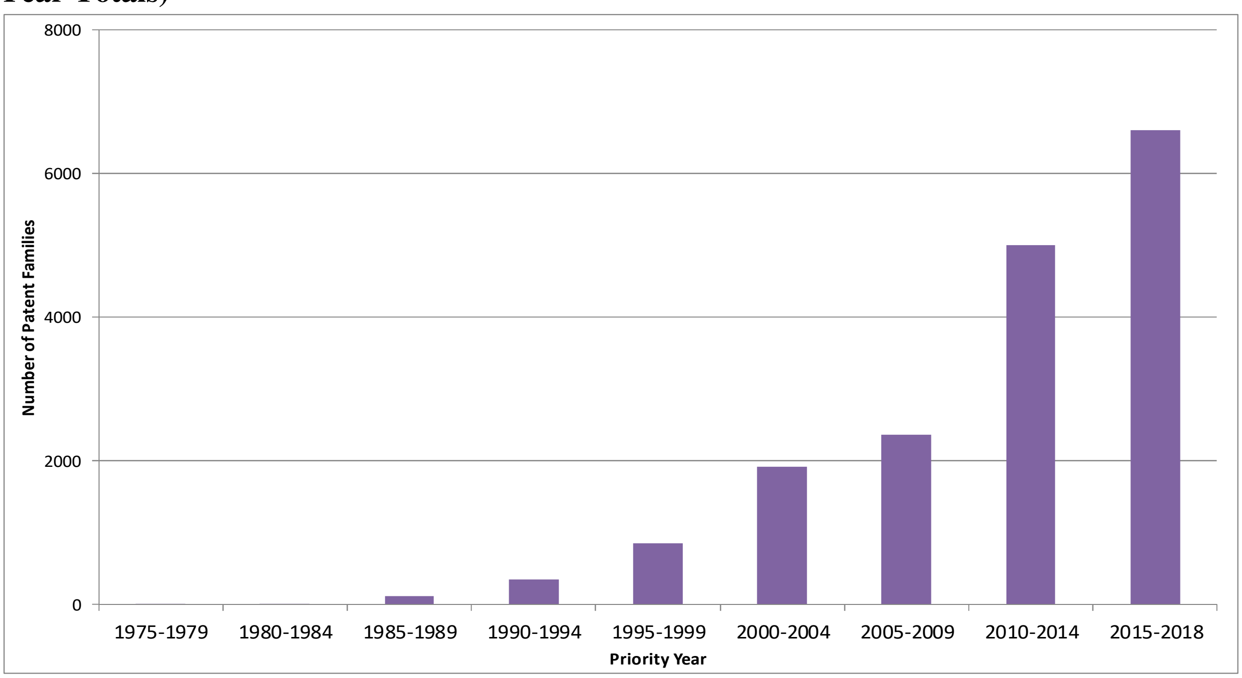
Comparing Figures 1 and 2 shows the effect of time lags in the patenting process, with many of the patent families with priority dates in 2005-2009 and 2010-2014 (Figure 1) resulting in granted U.S. patents in 2010-2014 and 2015-2019 (Figure 2). These time lags can also be seen in Figure 3, which shows additive manufacturing patent family priority years alongside issue years for granted U.S. additive manufacturing patents (in this figure, AMO and Other DOE are combined, in order to simplify the presentation). Early trends in both data series in this figure are very choppy, given the small numbers of documents involved. That said, it is possible to see how a spike in patent families filed in 2014-2015 led to U.S. patents increasing in 2016-2018. Due to the primary data collection period ending in 2018, the number of U.S. patents declines sharply in 2019 and the number of patent families is zero.

Figure 3 - Number of DOE-funded Additive Manufacturing 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 AMO. No new patent search for 2019 was carried out.

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

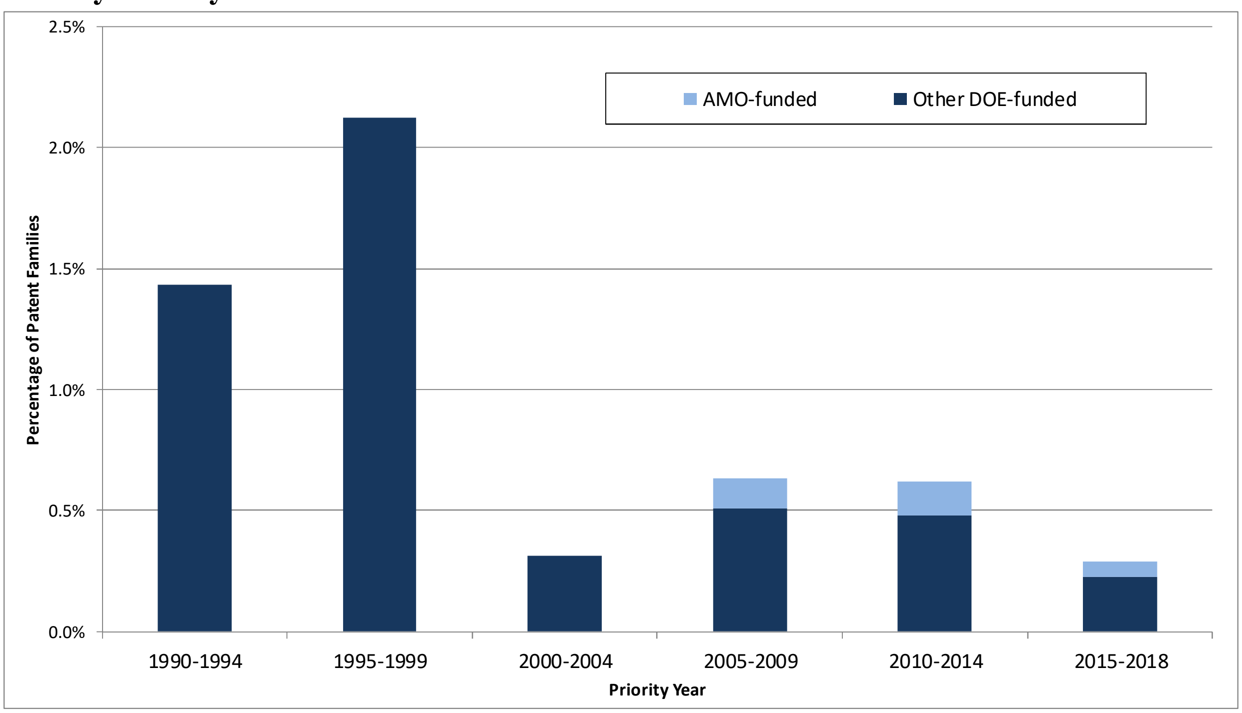


Note: The final time period in this figure is 2015-2018, and is shown for completeness, although data for this time period are incomplete. Our primary data collection covered only patents issued through 2018. Due to time lags associated with the patenting process, only a fraction of the patent families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

Figures 1-3 focus on DOE-funded additive manufacturing patent families. Figure 4 broadens the scope, and shows the overall number of additive manufacturing patent families by priority year (based on USPTO, EPO, and WIPO filings) from 1975 onwards. The number of patent families in the early time periods was very low, totaling 16 in 1975-1979 and 11 in 1980-1984. This number then started to increase, and has continued to grow in each time period since, reaching 6,608 patent families in 2015-2018, even though data for this period are incomplete (see note below Figure 4). Evaluating Figure 4 alongside Figure 1 thus suggests that the bulk of both overall and DOE-funded additive manufacturing patenting is concentrated primarily in the most recent time periods in the analysis.

Figure 5 shows the percentage of additive manufacturing patent families that were funded by DOE (AMO plus Other DOE). This percentage peaked at 2.1% in 1995-1999, all of them Other DOE-funded, although the numbers of patent families involved were relatively small. In more recent time periods, around 0.5% of patent families were funded by DOE (most of them Other DOE-funded). This lower percentage is not surprising, given the context of the rapid increase in overall additive manufacturing patenting. Overall, 0.5% of additive manufacturing patent families in the period 1976-2018 were funded by DOE.

Figure 5 - Percentage of Additive Manufacturing Patent Families Funded by AMO/Other DOE by Priority Year



Leading Additive Manufacturing Assignees

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

Figure 6 –Top 12 Additive Manufacturing Companies (based on number of patent families)

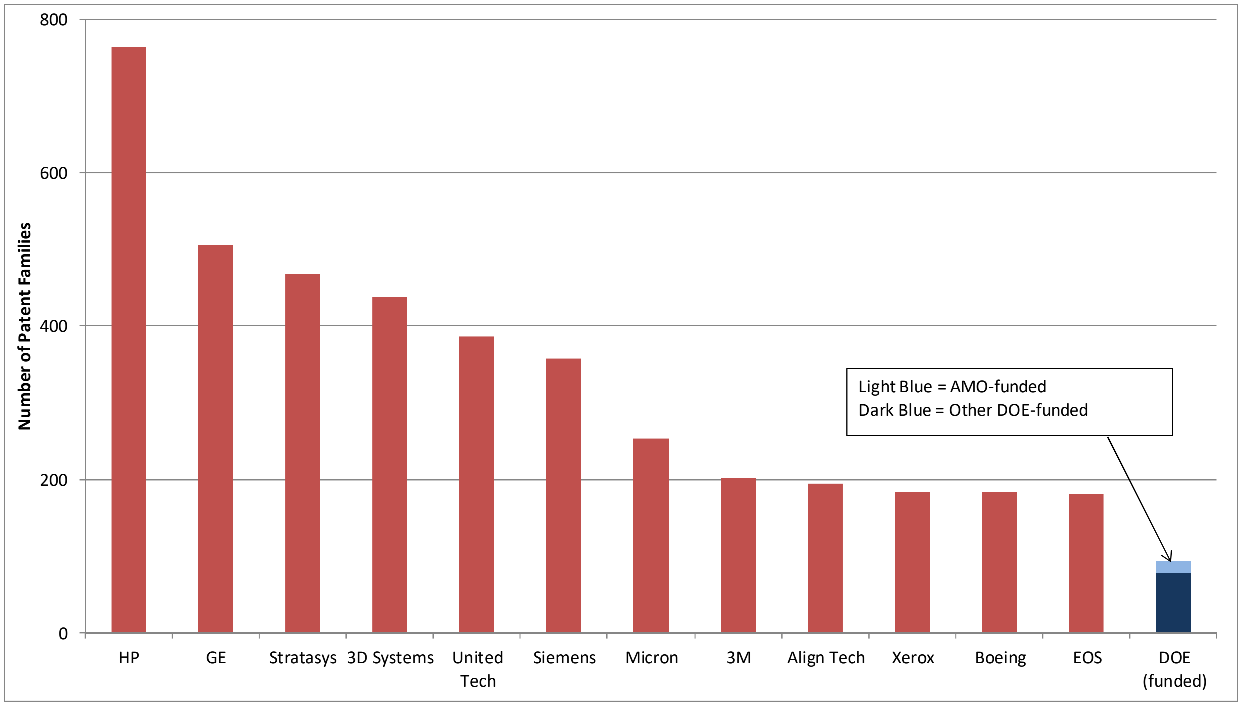


Figure 6 is headed by Hewlett-Packard with 764 additive manufacturing patent families, followed by General Electric (506 families) Stratasys (468 families) and 3D Systems (438 families). In general, the list of leading companies includes multinationals with interests in many different technologies (such as Hewlett Packard, General Electric, United Technologies, Siemens and 3M) and specialist companies with a particular focus on additive manufacturing (including Stratasys, 3D Systems and EOS). Figure 6 also reveals that the DOE-funded additive manufacturing portfolio of 92 patent families (14 AMO-funded; 78 Other DOE-funded) is smaller than those of the leading companies. In assessing the impact of AMO-funded and Other DOE-funded additive manufacturing patents, versus the impact of the patents associated with the leading companies, we thus take into account this difference in portfolio size.

It should be noted that there is a small amount of double-counting of patent families in Figure 6. Specifically, there is one United Technologies patent family that was partially or fully funded by AMO. There are also twelve General Electric patent families that are associated with Other DOE-funding. In Figure 6, the United Technologies patent family is counted in both the AMO-funded segment of the DOE column, and in the United Technologies column. Meanwhile, the General Electric patent families are counted in both the Other DOE-funded segment of the DOE column and in the General Electric column. This double-counting is appropriate, since these patent families are funded by DOE and also assigned to a leading company.

Assignees of AMO/Other DOE-funded Additive Manufacturing Patents

The DOE-funded additive manufacturing patent portfolios are constructed somewhat differently from the portfolios of the leading companies listed in Figure 6. Specifically, DOE's 92 patent families are those funded by DOE, but they are not necessarily assigned to the agency. For example, AMO (or another DOE office) may have funded research projects at DOE labs or companies. In such cases, the assignees of any resulting patents will be the respective DOE lab managers or companies (as in the case of the General Electric and United Technologies patent families discussed above).

Figure 7 shows the assignees on AMO-funded additive manufacturing patent families (given the small number of such families, all assignees are shown in this figure). This figure reveals that, out of the fourteen AMO-funded patent families, ten are assigned to UT-Battelle, through its management of Oak Ridge National Laboratory (ORNL). This suggests that ORNL has been a major center for AMO-funded additive manufacturing research. The remaining assignees in Figure 7 – United Technologies, IC Patterns, Fopat, and Consolidated Nuclear Security – each have one AMO-funded additive manufacturing patent family.

Figure 7 - Assignees of AMO-Funded Additive Manufacturing Patent Families

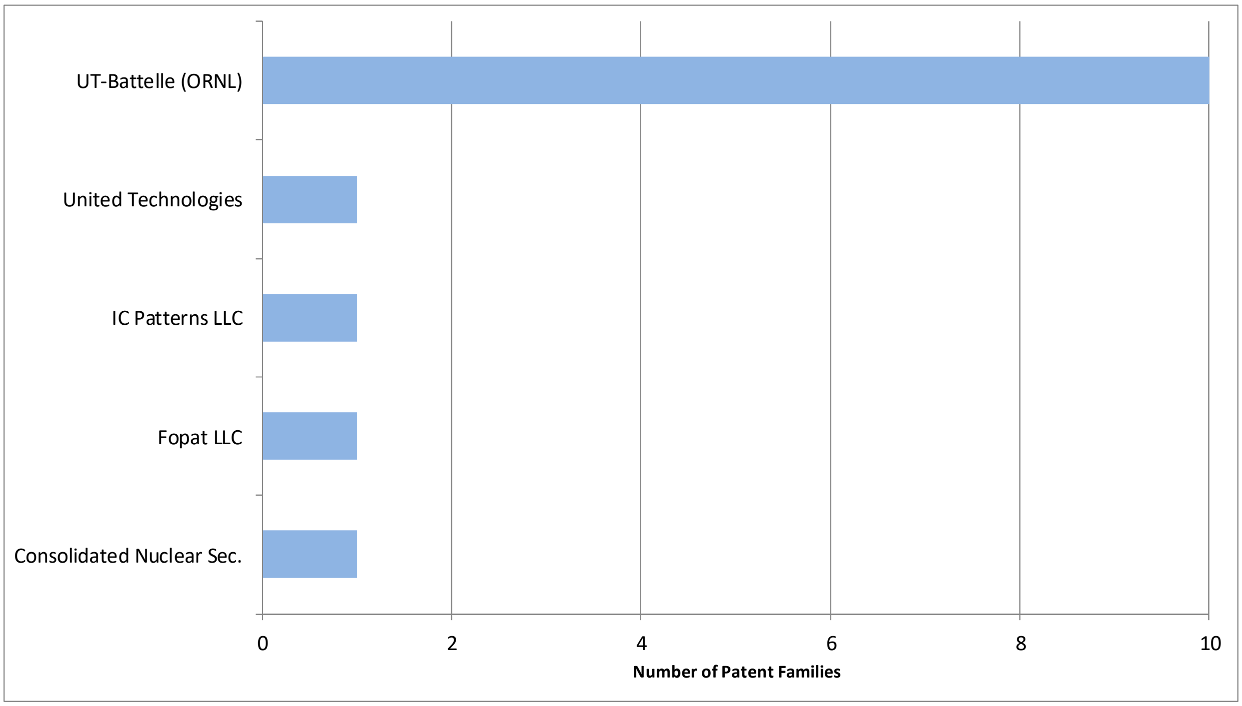
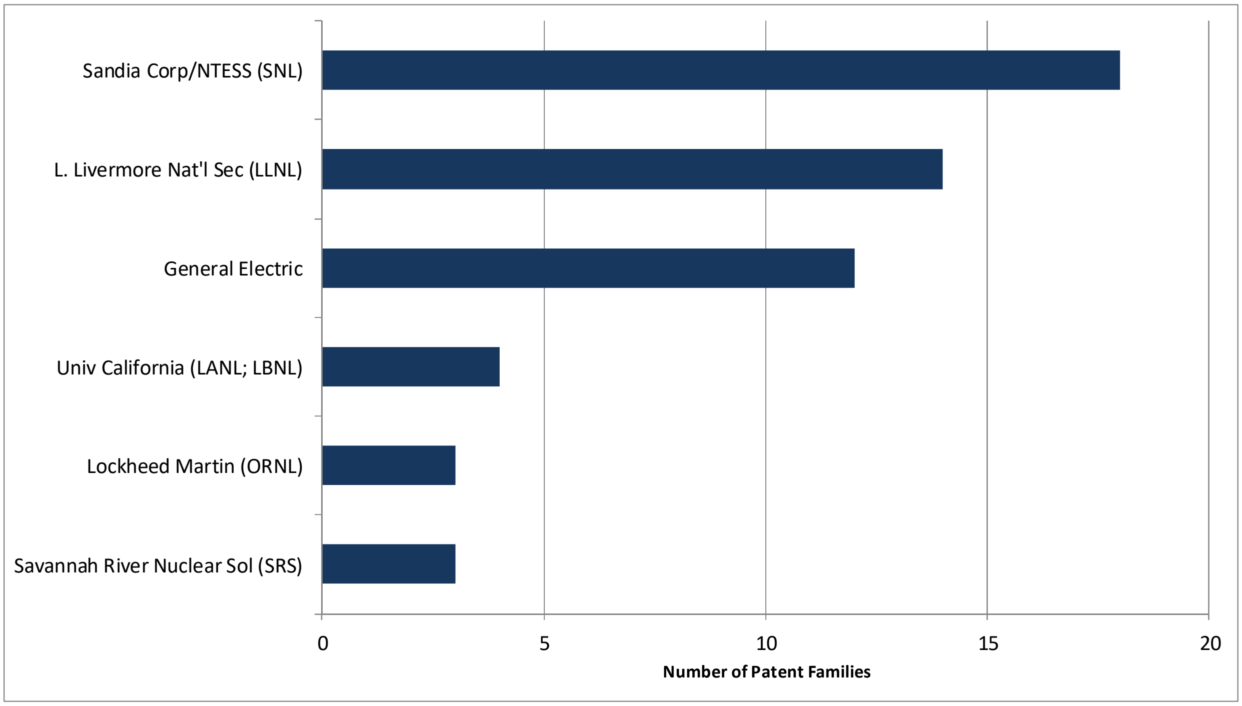


Figure 8 shows the leading assignees on Other DOE-funded additive manufacturing patent families. This figure is headed by two assignees associated with managing Sandia National Laboratory – Sandia Corporation and NTESS – with a combined total of 18 Other DOE-funded additive manufacturing patent families. They are followed by Lawrence Livermore National Security (Lawrence Livermore National Laboratory) with 14 patent families and General Electric (12 families). The other assignees in Figure 8 are DOE lab managers – University of California (Los Alamos National Laboratory and Lawrence Berkeley National Laboratory), Lockheed Martin (Oak Ridge National Laboratory) and Savannah River Nuclear Solutions (Savannah River Site).

Figure 8 – Leading Assignees on Other DOE-funded Additive Manufacturing Patent Families



Distribution of Additive Manufacturing Patents across Patent Classifications

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

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

Figure 9 - Percentage of Additive Manufacturing U.S. Patents in Most Common Cooperative Patent Classifications (Among AMO-Funded Patents)

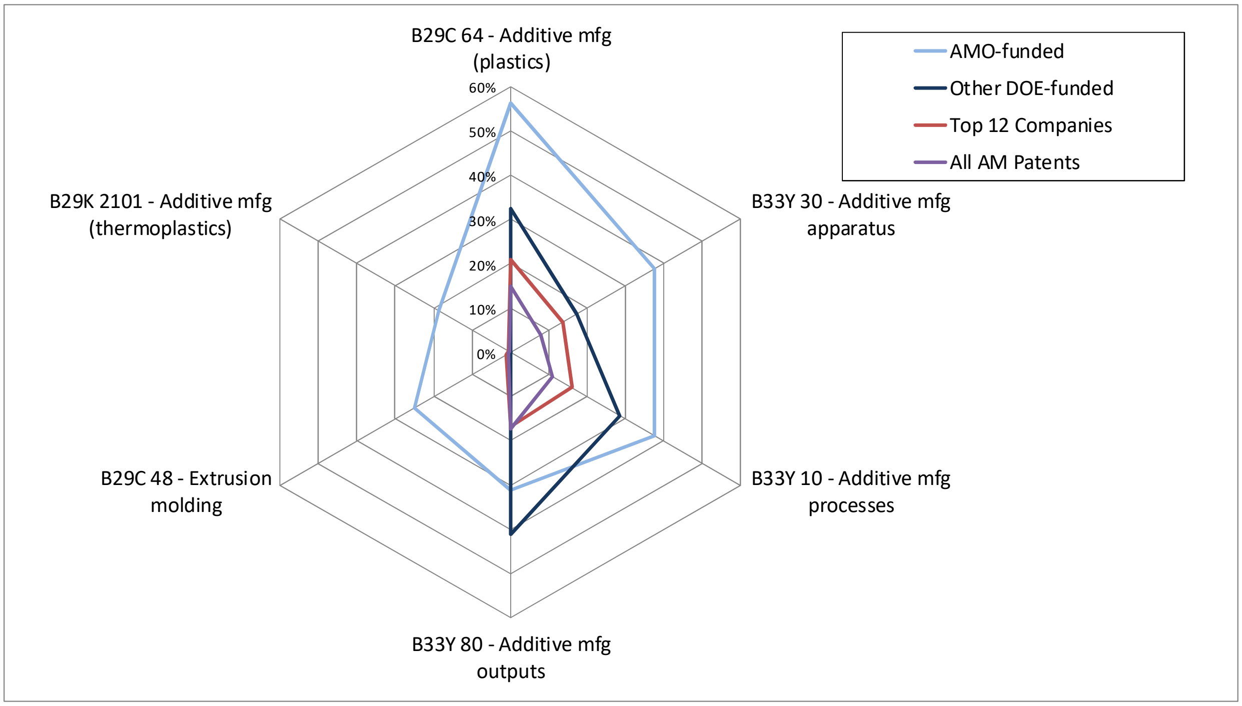


Figure 9 shows that AMO-funded research includes relatively balanced coverage across the six CPCs (which is not particularly surprising, since the AMO-funded patent portfolio forms the basis for the CPCs included in the chart). The most common CPC among AMO-funded additive manufacturing patents is B29C 64, which appears on 56% of these patents. This CPC is related to additive manufacturing using plastic materials. The other CPCs in Figure 9 are primarily concerned with different aspects of additive manufacturing, including apparatus (B33Y 30), processes (B33Y 10) and objects produced using additive manufacturing (B33Y 80). The other portfolios in Figure 9 also have a notable presence in these CPCs, although the percentages in each CPC are lower, which is not surprising given that they are much larger than the AMO-funded portfolio, and so less focused. Two CPCs where AMO-funded patents are present, but not the other portfolios, are B29K 2101 (Additive manufacturing with thermoplastics) and B29C 48 (Extrusion molding).

Figure 10 is similar to Figure 9, except that it is from the perspective of the most common CPCs among all additive manufacturing patents. Hence, the purpose of this chart is to show the main research areas within additive manufacturing as a whole, and how these areas are represented in selected additive manufacturing portfolios (AMO-funded; Other DOE-funded; leading additive manufacturing companies). Four of the six most common CPCs among all additive manufacturing patents in Figure 10 also appeared in Figure 9, and are concerned with various aspects of additive manufacturing technology. This suggests that the technological focus of AMO-funded patents is similar to additive manufacturing patents in general. The two new CPCs in Figure 10 (B33Y 50 and B33Y 70) are also related to additive manufacturing, specifically data management and materials respectively. AMO-funded patents have a smaller presence in these CPCs.

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

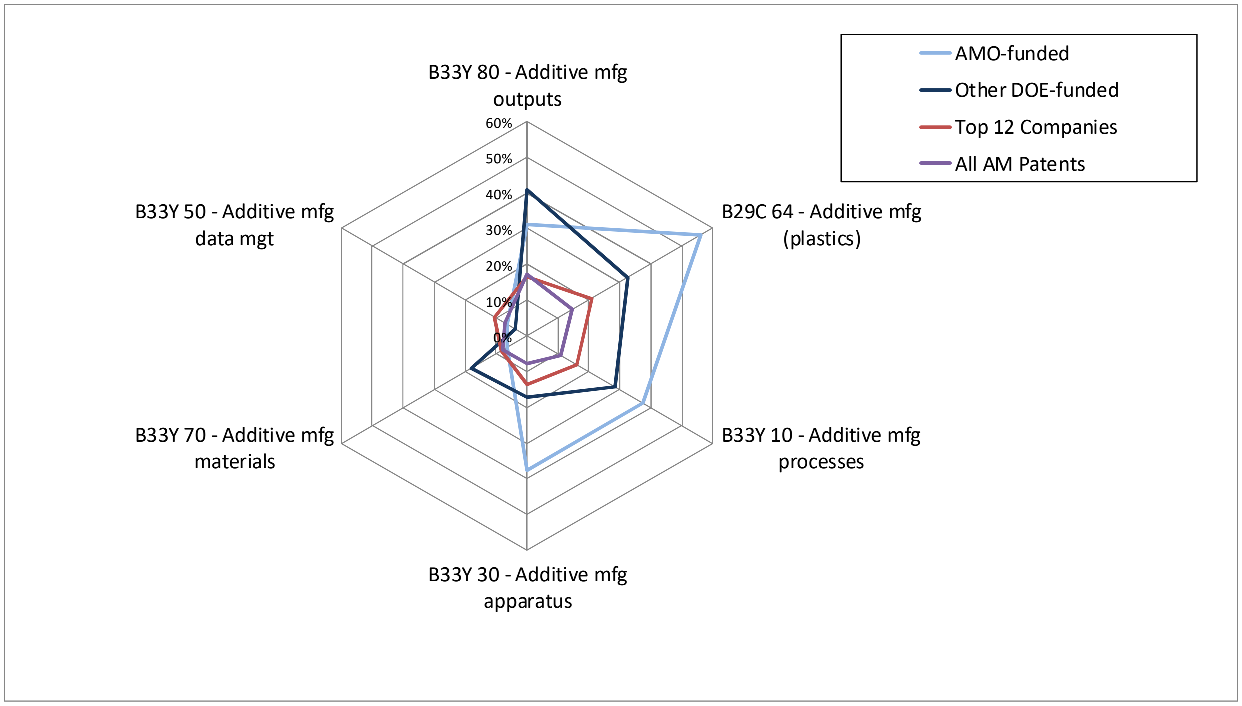


Figure 11 - Percentage of AMO-funded Additive Manufacturing U.S. Patents in Most Common Cooperative Patent Classifications across Two Time Periods

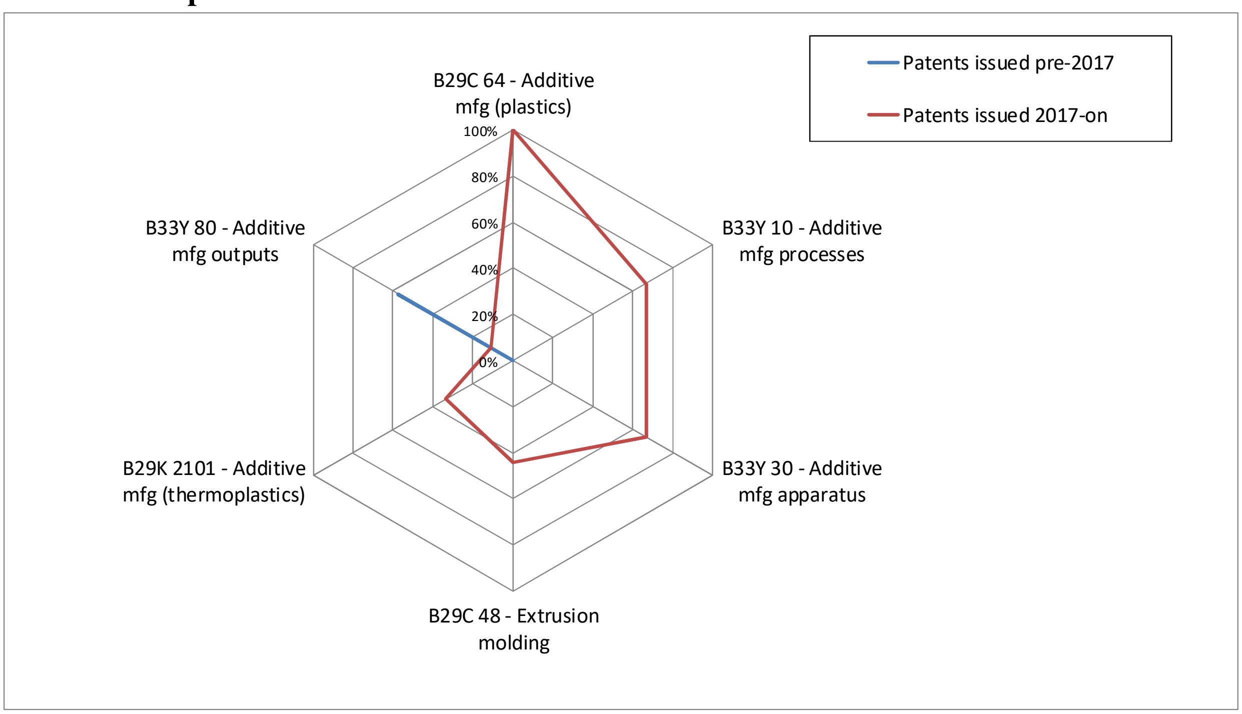


Figure 11 compares the CPC distribution of AMO-funded additive manufacturing U.S. patents across two time periods – patents issued through 2016, and those issued from 2017 onwards (these dates were selected to divide the patents into two groups of approximately equal size). This figure reveals a distinct shift in the CPC distribution across these two time periods. In the earlier time period, AMO-funded patent families were focused primarily on items produced using additive manufacturing (CPC B33Y 80). In the more recent period, AMO-funded patents are divided much more evenly across different aspects of additive manufacturing (note that this could be due in part to a change in the approach taken by the patent office in allocating CPCs to additive manufacturing inventions, given that this is an evolving technology field).

Tracing Backwards from Additive Manufacturing Patents Owned by Leading Companies

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

Organizational Level Results

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

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

In total, 559 leading company additive manufacturing patent families (i.e. 13.6% of these 4,113 families) are linked via citations to earlier DOE-funded additive manufacturing patents, out of

[8] This figure compares the influence of patents *funded* by AMO/Other DOE against patents *owned* by (i.e. assigned to) organizations. Such a comparison is reasonable, since patents funded by organizations through their R&D budgets will be assigned to those organizations. Also, organizations cannot choose to reference the patents of a non-competitor (such as DOE) rather than the patents of a competitor in order to reduce the "credit" given to that competitor. Such an omission could lead to the invalidation of their patents. Note that, as in Figure 6, there is a small amount of double-counting in Figure 12 and Figure 13, as some patent families assigned to General Electric and United Technologies were funded by DOE. Also, in Figures 12 and 14-16, leading company patent families linked to both AMO-funded and Other DOE-funded patents are allocated to the AMO-funded segment of the DOE column, in order to avoid double-counting these families.

which only three are linked to AMO-funded additive manufacturing patents. This reflects the fact that there is a much longer history of Other DOE-funded additive manufacturing patents, with AMO-funded patents being a much smaller portfolio concentrated in the most recent time periods. As such, there has been relatively little time for AMO-funded patent families to become linked via citations to subsequent generations of technology.

DOE-funded patent families are in sixth place in Figure 12. The figure is headed by 3D Systems, with 1,766 leading company patent families linked to its earlier patents, followed by Stratasys (1,212 linked families), United Technologies (866 linked families) and EOS (821 linked families). That said, it should be noted that Figure 12 does not take into account the different sizes of the patent portfolios associated with the various companies. Hence, it is not surprising that these companies have more patent families linked to them via citations than does DOE, since they have more patents available to be cited as prior art.

Figure 12 - Number of Leading Company Additive Manufacturing Patent Families Linked via Citations to Earlier Additive Manufacturing Patents from each Leading Company
e.g. 559 leading company families are linked to earlier AMO/Other DOE-funded families

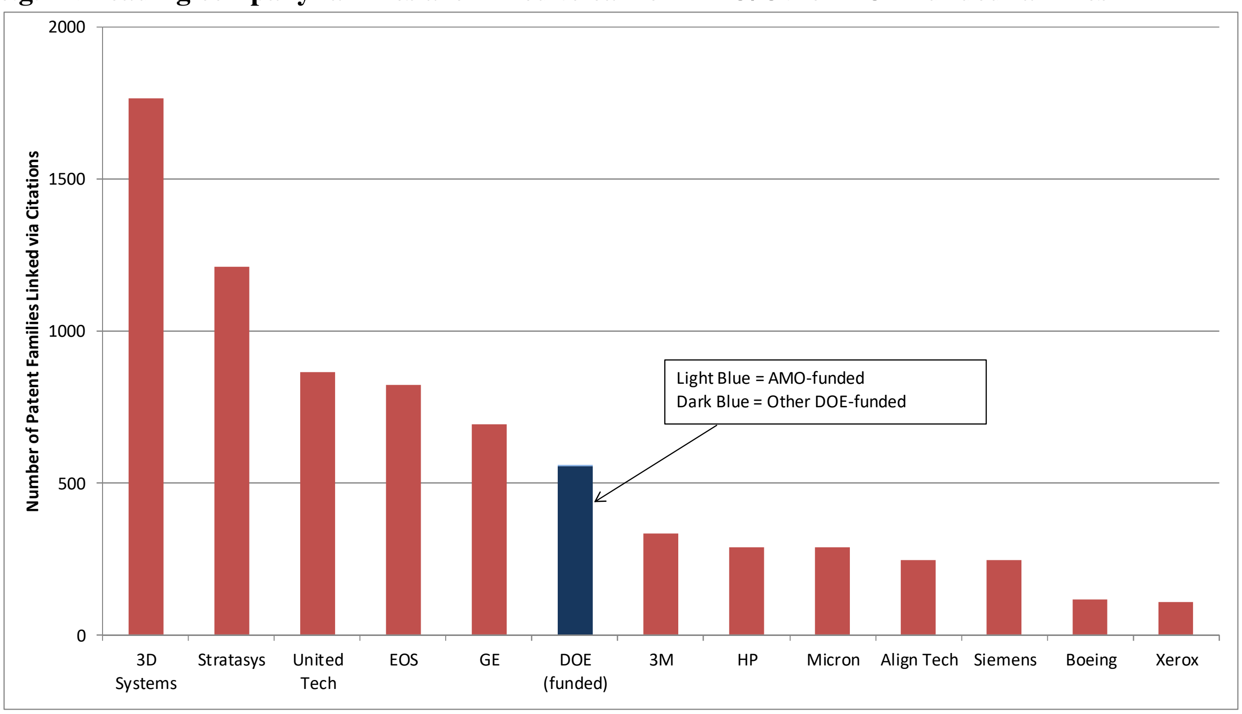
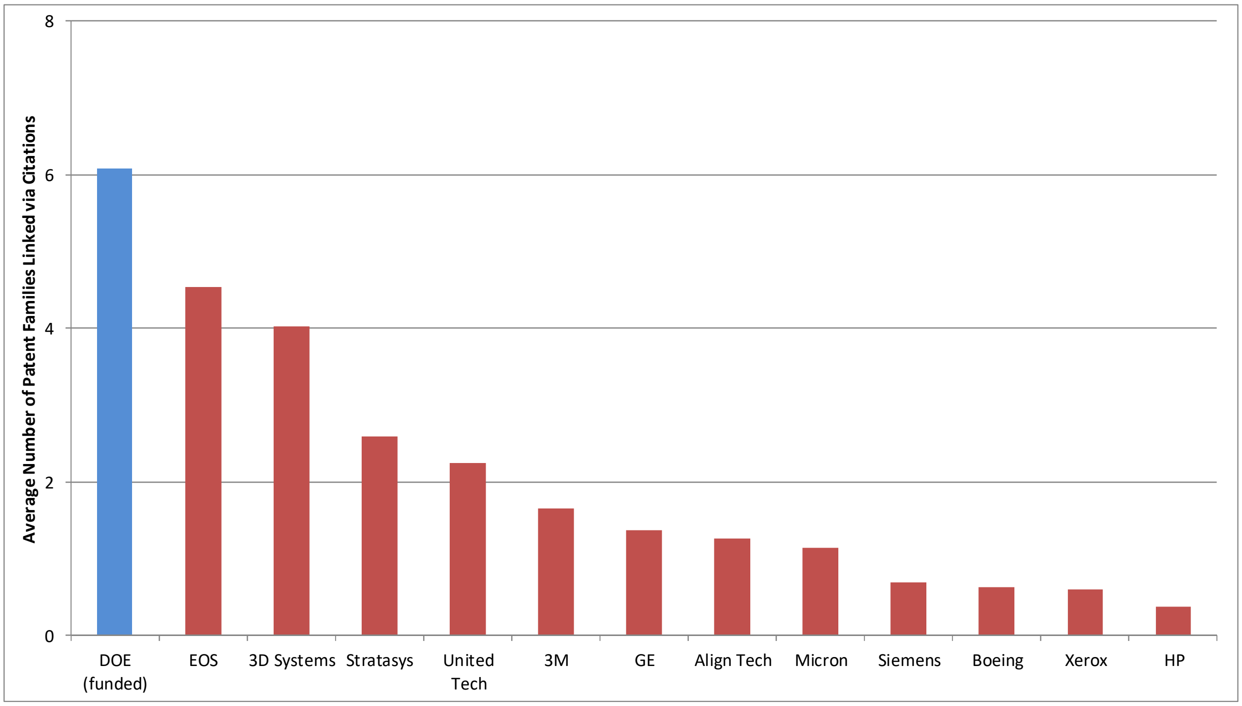


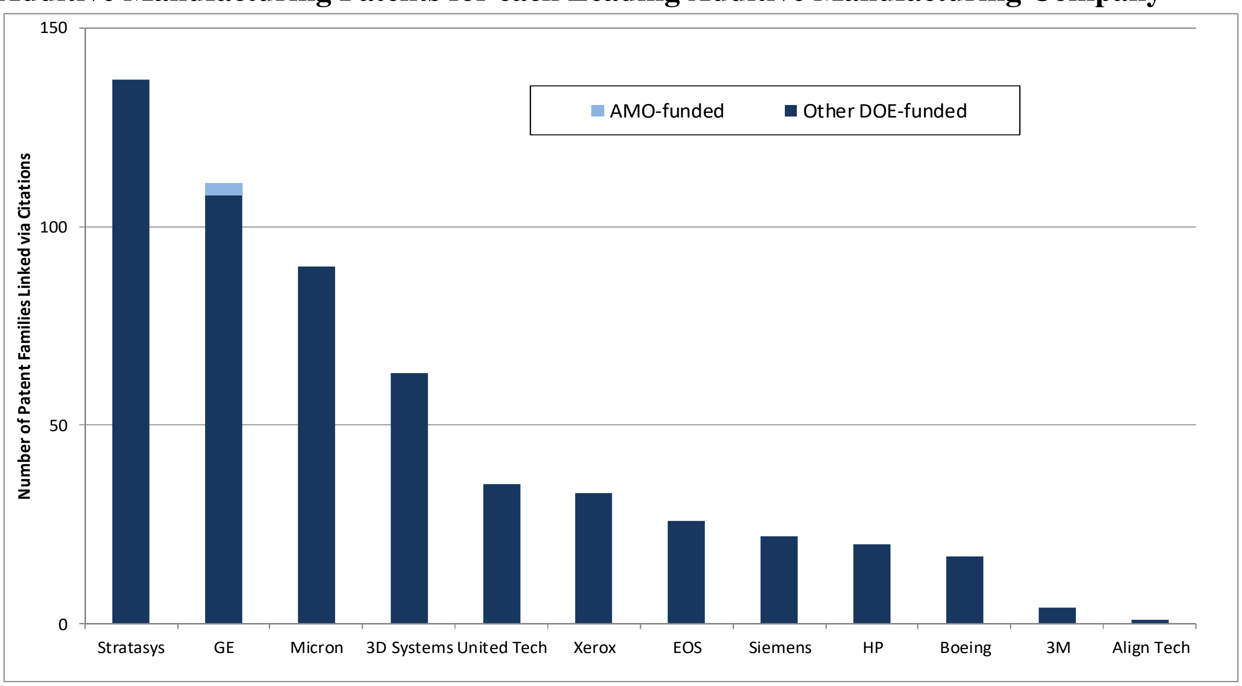
Figure 13 takes into account the differences in patent portfolio size. It shows the average (mean) number of leading company patent families linked via citations to patent families associated with each of the leading companies, plus DOE. For example, on average, DOE-funded additive manufacturing patent families are each linked to over six patent families assigned to the leading companies. This puts DOE at the head of Figure 13. It means that, on average, more additive manufacturing patent families owned by leading companies are linked via citations to each DOE-funded patent family than are linked to the patent families assigned to any other leading company. Figure 13 thus suggests that, taking into account its relatively small size, the portfolio of DOE-funded additive manufacturing patents has helped form an important part of the foundation for additive manufacturing innovations associated with the leading companies.

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



Figures 14 through 16 examine which of the leading companies build most extensively on earlier DOE-funded patents. Figure 14 shows how many additive manufacturing patent families owned by each of the leading companies are linked via citations earlier DOE-funded patents.

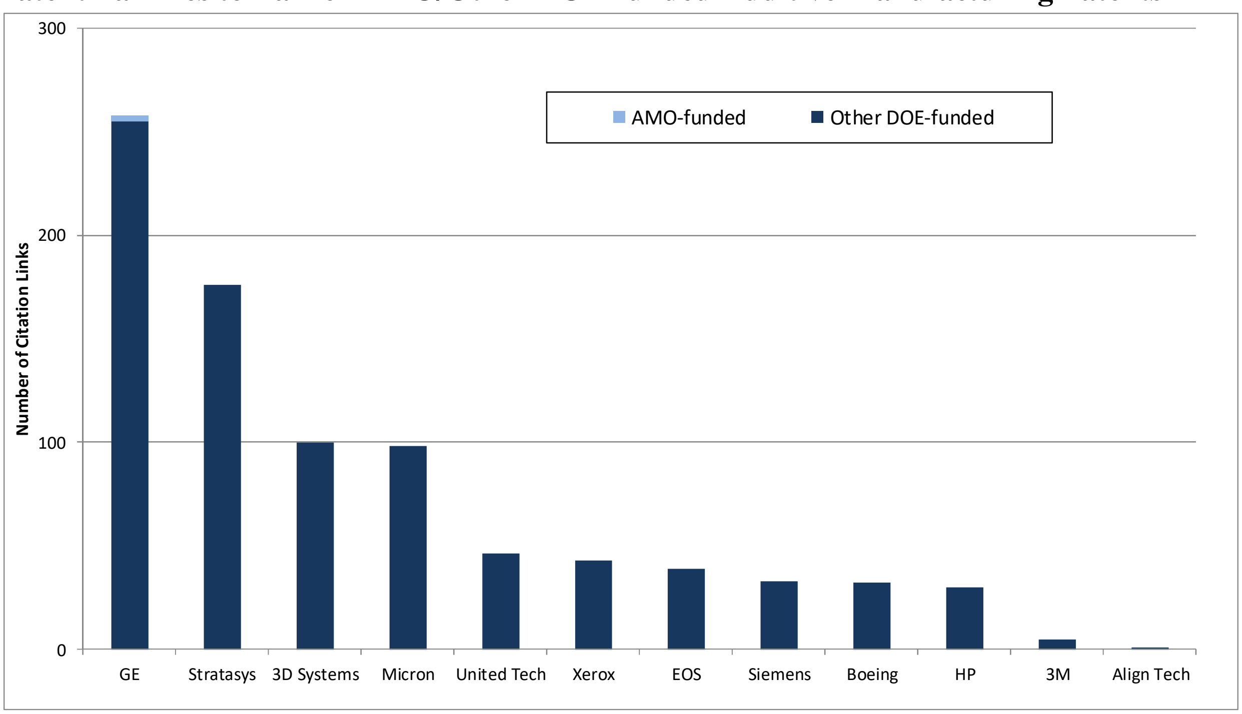
Figure 14 – Number of Patent Families Linked via Citations to Earlier DOE-funded Additive Manufacturing Patents for each Leading Additive Manufacturing Company



All twelve of the leading additive manufacturing companies have at least one patent family linked via citations to earlier DOE-funded patents. Stratasys is at the head of Figure 14, with 137 patent families linked via citations to DOE, with all of these links being to Other DOE-funded patents. General Electric is in second place, with 108 patent families linked via citations to DOE, three of which are linked to AMO-funded patents. Indeed, General Electric is the only company in Figure 14 with patent families linked via citations to earlier AMO-funded patents. This again reflects the finding reported earlier, that the Other DOE-funded additive manufacturing patent portfolio is both much larger and more established than the AMO-funded portfolio, and so is linked via citations to many more leading company patents. General Electric is followed in Figure 14 by Micron and 3D Systems, with 90 and 63 patent families respectively linked via citations to earlier Other DOE-funded patents.

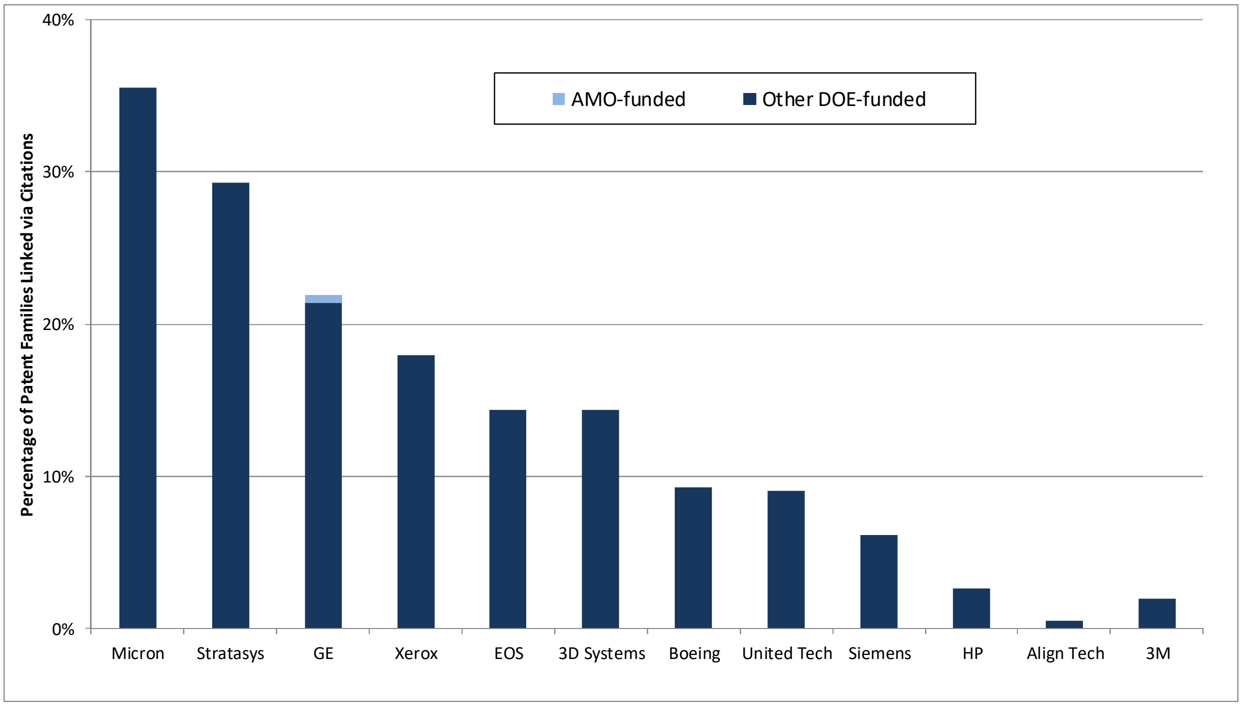
Figure 15 counts the total number of citation links from leading companies to earlier DOE-funded patents. This differs slightly from the count of linked families in Figure 14, since a single patent family may be linked to multiple earlier DOE-funded patents. The four companies at the head of Figure 14 – Stratasys, General Electric, Micron and 3D Systems – are again at the head of Figure 15. The biggest difference between the figures is that General Electric has the largest number of citation links to DOE-funded patents (258), ahead of Stratasys (176), 3D Systems (100) and Micron (98).

Figure 15 - Number of Citation Links from Leading Additive Manufacturing Company Patent Families to Earlier AMO/Other DOE-funded Additive Manufacturing Patents



There is an element of portfolio size bias in the patent family counts in Figures 14 and 15. Companies with larger additive manufacturing patent portfolios are likely to have more patent families linked to DOE, simply because they have more families overall. Figure 16 accounts for this portfolio size bias by calculating the percentage of each leading company's additive manufacturing patent families that are linked via citations to earlier DOE-funded additive manufacturing 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. Micron and Stratasys are at the head of Figure 16, with 36% and 29% of their additive manufacturing patent families linked via citations to earlier DOE-funded patents respectively (all of these links are to Other DOE-funded patents). They are followed by General Electric (22%) Xerox (18%) and EOS (14%), with the latter two companies becoming more prominent once patent portfolio sizes are taken into account.

Figure 16 - Percentage of Leading Additive Manufacturing Company Patent Families Linked via Citations to Earlier AMO/Other DOE-funded Additive Manufacturing 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 AMO-funded and Other DOE-funded additive manufacturing patent families that have influenced subsequent patents owned by the leading companies. Looking in the opposite direction, it also identifies individual additive manufacturing patents owned by the leading companies that are linked to earlier DOE-funded research.

The organizational-level results revealed that there are three leading company patent families linked via citations to earlier AMO-funded additive manufacturing patent families (see Figure 12). Examining the data at the individual patent level reveals that all three of these leading company families are linked to the same AMO-funded patent family. This patent family (whose representative patent[9] is US #9,650,537) is shown in Table 5. It was filed in 2014 by UT-Battelle, and describes reactive polymers for use in additive manufacturing.

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

Table 5 – AMO-Funded Additive Manufacturing Patent Families Linked via Citations to Subsequent Leading Company Additive Manufacturing Patent Families

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
54264569	9650537	2014	3	UT-Battelle	Reactive polymer fused deposition manufacturing

Table 6 lists the Other DOE-funded additive manufacturing patent families linked via citations to the largest number of subsequent families assigned to the leading companies. The patent family at the head of this table (representative patent US #5,837,960) was filed in 1995 and assigned to the University of California, through its management of Los Alamos National Laboratory. It describes directed light fabrication (DLF), used to produce objects from powders. This family is linked via citations to 321 patent families assigned to the leading companies (i.e. 8% of these 4,113 families are linked to the Los Alamos patent family). These include families assigned to eleven out of these twelve companies – all except Align Technology. Sandia Corporation has a number of patent families in Table 6, resulting from its management of Sandia National Laboratory. These include the family in second place in 1996 (representative patent US #6,046,426), which was filed in 1996 and describes production of objects via laser deposition of powders. This family is linked via citations to 121 subsequent patent families assigned to the leading companies, again including families assigned to all of these companies except Align. The third-place patent family in Table 6 (representative patent US #5,697,043) is assigned to Battelle Memorial Institute, the manager of Pacific Northwest National Laboratory. This patent family, which is linked to 102 families assigned to eight out of the twelve leading companies, outlines freeform fabrication, especially for ceramics.

Table 6 - Other DOE-Funded Additive Manufacturing Patent Families Linked via Citations to Most Subsequent Leading Company Additive Manufacturing Families

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
26670148	5837960	1995	321	Univ California (LANL)	Laser production of articles from powders
24714964	6046426	1996	121	Sandia Corp (SNL)	Method and system for producing complex-shape objects
24618545	5697043	1996	102	Battelle Memorial Inst (PNNL)	Method of freeform fabrication by selective gelation of powder suspensions
23557909	6459951	1999	59	Sandia Corp (SNL)	Direct laser additive fabrication system with image feedback control
25228675	6080343	1997	42	Sandia Corp (SNL)	Methods for freeform fabrication of structures
25501511	6027326	1997	38	Sandia Corp (SNL)	Freeforming objects with low-binder slurry
25445399	6107008	1997	29	Lockheed Martin (ORNL)	Ionizing radiation post-curing of objects produced by stereolithography and other methods
25453925	5975493	1997	18	Univ Chicago (ANL)	Process for controlling flow rate of viscous materials including use of a nozzle with changeable opening
22131799	6143378	1998	18	Sandia Corp (SNL)	Energetic additive manufacturing process with feed wire
37186024	7419630	2005	17	Sandia Corp (SNL)	Methods and systems for rapid prototyping of high density circuits

Table 7 looks in the opposite direction to Tables 5 and 6, and lists the additive manufacturing patent families owned by leading companies that are linked via citations to the most earlier AMO-funded and Other DOE-funded patents. The three patent families at the top of this table are all assigned to General Electric (e.g. representative patent US #9,956,612) and describe large-scale additive manufacturing techniques. Each is linked to six DOE-funded patent families, including the AMO-funded family shown in Table 5. Stratasys has the patent family in fourth place in Table 7 (representative patent US #8,512,024), which is linked via citations to four earlier Other DOE-funded families. This Stratasys family outlines an additive manufacturing device with multiple extrusion drive motors. Other patent families in Table 7 (each of which is linked to at least three DOE-funded families) are assigned to various leading companies, reflecting the influence of DOE-funded additive manufacturing patents across these companies.

Table 7 - Leading Company Additive Manufacturing Patent Families Linked via Citations to Largest Number of DOE-Funded Additive Manufacturing Patent Families

Patent Family #	Representative Patent #	Priority Year	# DOE (AMO) Fams	Assignee	Title
62016722	9956612	2017	6 (1)	General Electric	Additive manufacturing using a mobile scan area
62837366	10022794	2017	6 (1)	General Electric	Additive manufacturing using a mobile build volume
62837363	10022795	2017	6 (1)	General Electric	Large scale additive machine
46544350	8512024	2011	5 (0)	Stratasys	Multi-extruder
54768863	9738032	2014	4 (0)	Xerox	System for controlling operation of a printer during three-dimensional object printing
55358592	10029417	2014	4 (0)	Siemens	Articulating build platform for laser additive manufacturing
54771028	9878493	2014	4 (0)	Xerox	Spray charging and discharging system for polymer spray deposition device
39710671	7968626	2008	3 (0)	3D Systems	Three dimensional printing material system and method using plasticizer-assisted sintering
36790858	7850885	2005	3 (0)	Electro Optical Systems	Device and method for manufacturing a three-dimensional object with a heated recoater
32824828	7306758	2003	3 (0)	HP	Methods and systems for controlling printhead temperature in solid freeform fabrication
39486829	7810552	2006	3 (0)	Boeing	Method of making a heat exchanger

Beyond locating the leading company patent families with the most extensive citation links to earlier DOE-funded patents, we also located high-impact patents owned by these leading companies that have citation links to DOE-funded patents.[10] The idea is to highlight important

[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 B33Y 10 (Additive manufacturing processes) 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

technologies owned by leading companies that are linked to earlier additive manufacturing research funded by DOE.

Table 8 lists additive manufacturing patents owned by the leading companies that have Citation Index values above three (i.e. they have been cited at least three times more frequently than expected), and are linked via citations to earlier DOE-funded additive manufacturing patents (all are linked to Other DOE-funded rather than AMO-funded patents). This table is headed by a Stratasys patent (US #8,488,994) describing an additive manufacturing system using electrophotography. Since being issued in 2013, this patent has been cited as prior art by 67 subsequent patents, more than 27 times as many citations as expected given its age and technology. 3D Systems has three of the next four patents in Table 8, each of which describes 3D printers. For example, patent US #7,291,002 has been cited by 95 subsequent patents since it was issued in 2007, more than thirteen as many citations as expected. EOS also has two highly-cited patents in Table 8 (e.g. US #7,153,463) describing treating powders for 3D printing.

Table 8 - Highly Cited Leading Company Additive Manufacturing Patents Linked via Citations to Earlier DOE-funded Additive Manufacturing Patents

Patent	Issue Year	# Cites Received	Citation Index	Assignee	Title
8488994	2013	67	27.74	Stratasys	Electrophotography-based additive manufacturing system with transfer-medium service loops
7291002	2007	95	13.77	3D Systems	Apparatus and methods for 3D printing
6989115	2006	98	10.80	3D Systems	Method and apparatus for prototyping a three-dimensional object
6749414	2004	110	10.76	Stratasys	Extrusion apparatus for three-dimensional modeling
7435368	2008	59	7.90	3D Systems	Three-dimensional printer
7153463	2006	70	7.00	Electro Optical Systems	Device for treating powder for a device which produces a three-dimensional object
6672343	2004	76	5.29	Electro Optical Systems	Device for supplying powder for a device for producing a three-dimensional object layer by layer
6984545	2006	50	3.94	Micron Technology	Methods of encapsulating selected locations of a semiconductor die assembly using a thick solder mask
7236166	2007	63	3.60	Stratasys	High-resolution rapid manufacturing

Overall, the backward tracing element of the analysis shows that patents assigned to the leading additive manufacturing companies have strong citation links to earlier DOE-funded patents. Most of these citation links are to Other DOE-funded, rather than AMO-funded, patents. This reflects the fact that the Other DOE-funded additive manufacturing patent portfolio is much larger than the AMO-funded portfolio, and also contains older patents that have had a longer period over which to become linked to subsequent leading company innovations.

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.

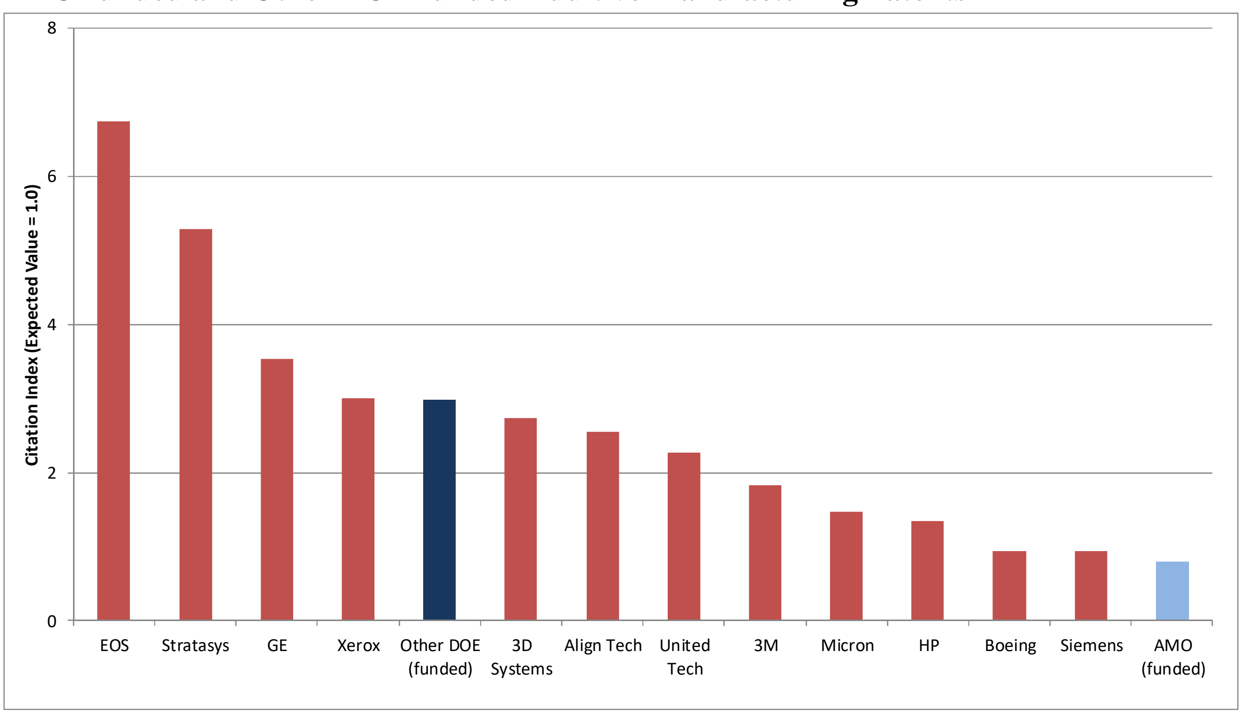
Tracing Forwards from DOE-funded Additive Manufacturing Patents

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

Organizational Level Results

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

Figure 17 - Citation Index for Leading Companies' Additive Manufacturing Patents, plus AMO-funded and Other DOE-funded Additive Manufacturing Patents

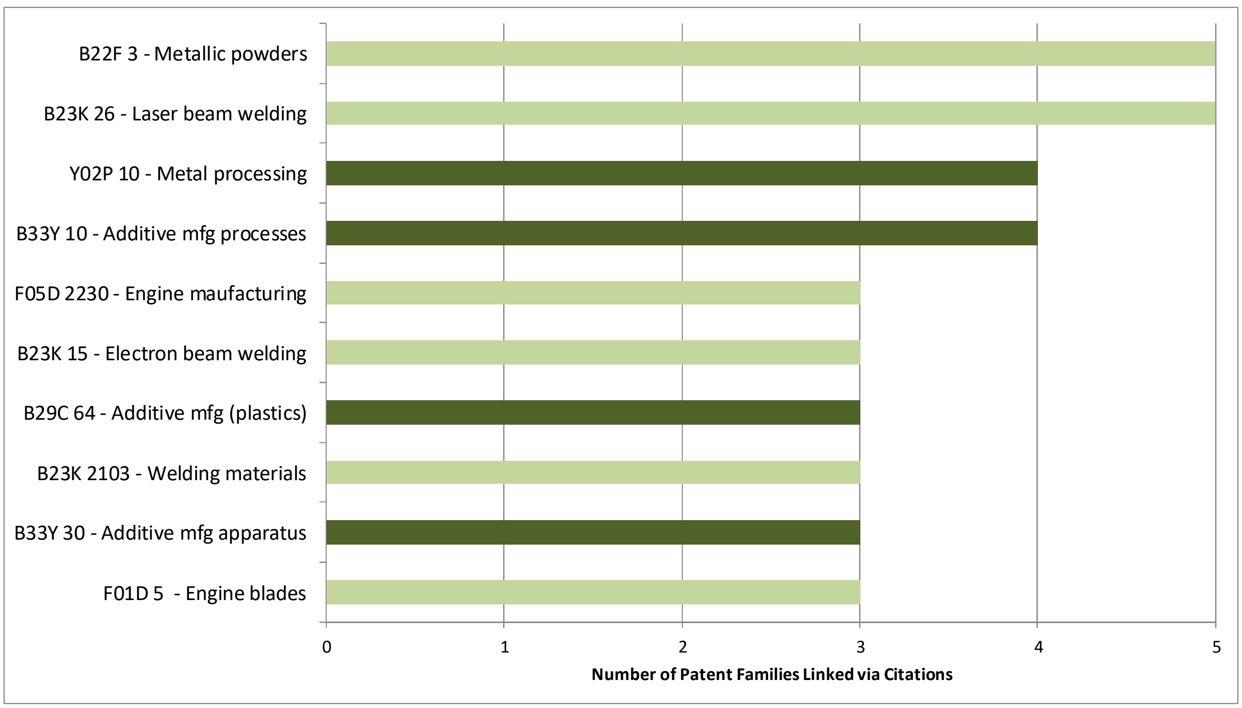


This figure is headed by EOS with a an average Citation Index of 6.75, showing that its patents have been cited as prior art almost seven times as frequently as expected, given their age and technology. Stratasys is in second place with a Citation Index of 5.30, followed by General

Electric (3.54) and Xerox (3.01). Other DOE-funded patents are in fifth place, with their average Citation Index of 2.99 showing that they have been cited almost three times as frequently as expected. AMO-funded patents have a much lower Citation Index of 0.79 (i.e. 21% fewer citations than expected). That said, as discussed in the backward tracing element of the analysis, many of the AMO-funded patents are relatively recent, so the number of citations they have received (and their associated expected citation rates) are still very low.

The Citation Index measures the overall influence of the DOE-funded additive manufacturing patent portfolios, but does not 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 additive manufacturing patent families.[11] These CPCs reflect the influence of DOE-funded research across technologies. Figure 18 lists the CPCs with the largest number of patent families linked via citations to AMO-funded additive manufacturing patents. The CPCs are shown in two different colors according to whether or not they are related to additive manufacturing technology. The former represent the influence of AMO-funded patents on additive manufacturing technology itself, while the latter represent spillovers of the influence of AMO-funded additive manufacturing research into other technology areas (although the numbers of patent families in this figure are only small).

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



[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 additive manufacturing patent families.

Four of the ten CPCs in Figure 18 are related to additive manufacturing. The most prominent of these CPCs are Y02P 10 (Metal processing, including via additive manufacturing) and B33Y 10 (Additive manufacturing processing), with four patent families in each CPC linked via citations to earlier AMO-funded patents. The two CPCs at the head of Figure 18 are related to metallic powders (B22F 3) and laser beam welding (B23K 26), with five patent families in each of these CPCs linked via citations to AMO-funded patents. These are technologies that are adjacent to, but not necessarily exclusive to, additive manufacturing. They are among a number of CPCs in Figure 18 connected to metals processing and engine manufacturing, suggesting that these are technologies where it is possible to trace the influence of AMO-funded research.

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

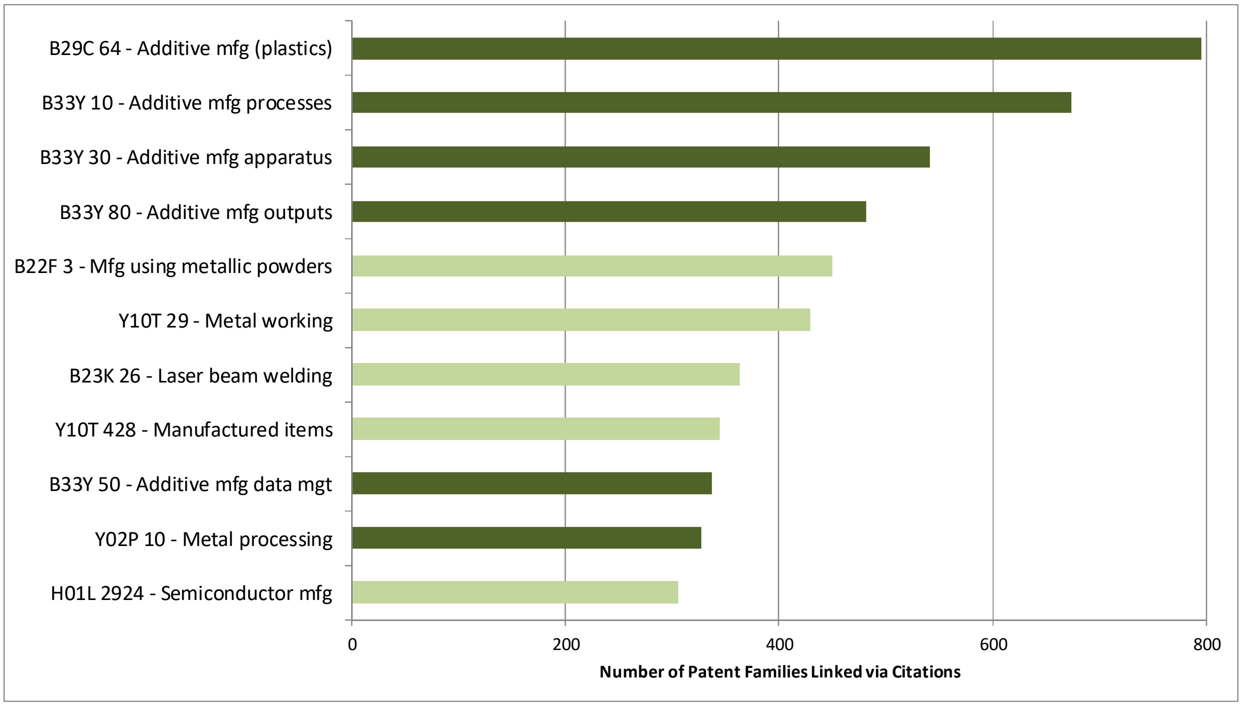


Figure 19 is similar to Figure 18, but is based on patent families linked to Other DOE-funded additive manufacturing patents, rather than AMO-funded additive manufacturing patents. Again, the CPCs are shown in two colors depending on whether or not they are related to additive manufacturing technology. Note that the numbers of patent families in this figure are much higher than those in Figure 18. Six of the eleven CPCs in Figure 19 are concerned with various aspects of additive manufacturing, including processes (B33Y 10), apparatus (B33Y 30), items produced (B33Y 80), and the use of plastics in additive manufacturing (B29C 64). Looking beyond additive manufacturing, CPCs related to metals processing (e.g. B22F 3 and Y10T 29) are again prominent in Figure 19. There is also a CPC in this figure related to semiconductor manufacturing (H01L 2924).

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

Figure 20 is headed by Saudi Basic Industries (SABIC), a leading chemical company and subsidiary of the state-owned Saudi Aramco. It has five patent families in Figure 20, describing copolymer-based additive manufacturing systems, and items produced by these systems. These SABIC patent families are linked via citations to an earlier UT-Battelle patent family (representative patent US #8,951,303) describing robotic or prosthetic components produced using additive manufacturing techniques. Rolls-Royce is in second place in Figure 20 with three patent families describing articles capable of withstanding high thermal loads. These Rolls-Royce families are linked via citations to earlier AMO-funded patents assigned to United Technologies and Fopat Inc. for turbine manufacturing and casting materials respectively. The remaining organizations in Figure 20 each have only one patent family linked via citations to AMO-funded additive manufacturing patents.

Figure 20 - Organizations with Patent Families Linked via Citations to AMO-funded Additive Manufacturing Patents (excluding leading additive manufacturing companies)

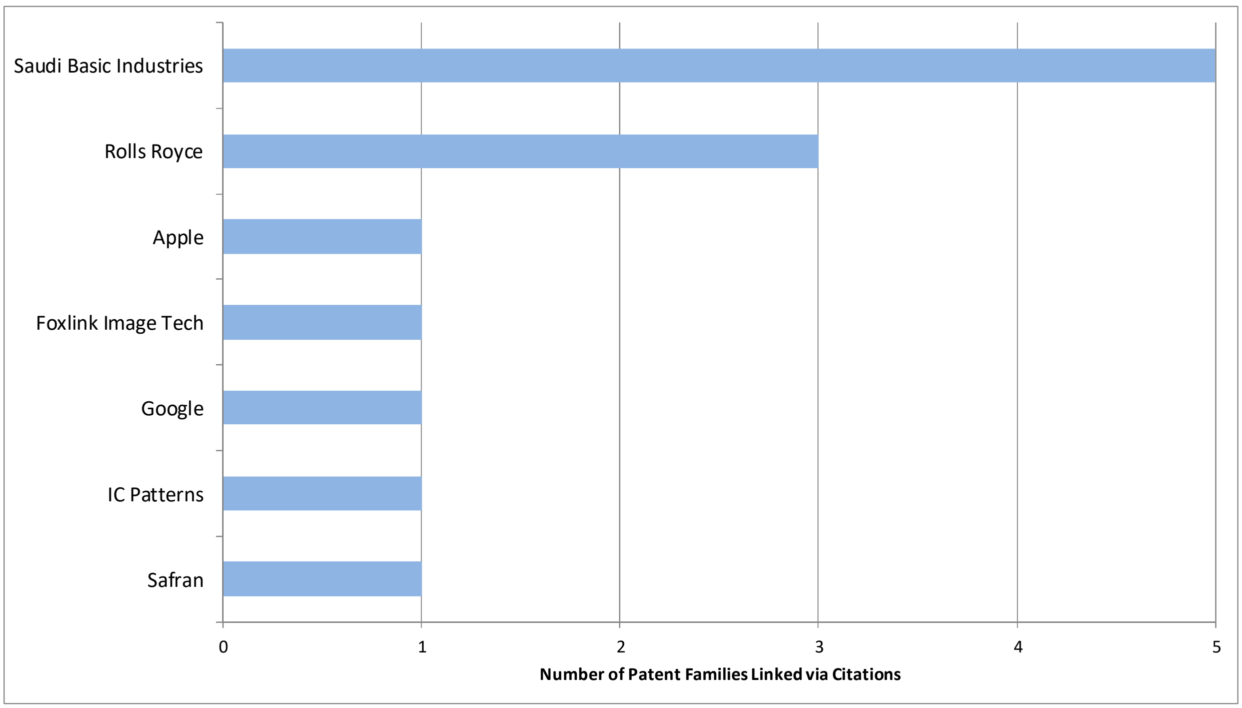
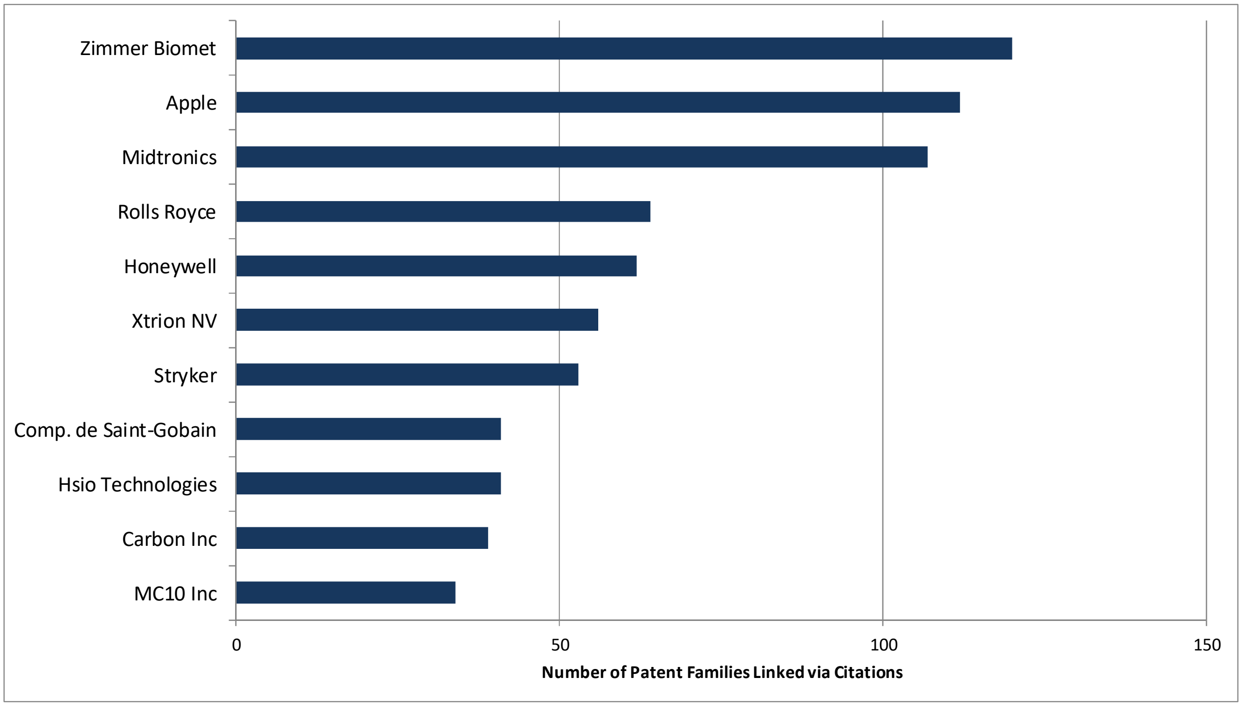


Figure 21 shows the organizations with the largest number of patent families linked via citations to earlier Other DOE-funded additive manufacturing patents. The three companies at the head of this figure each have more than 100 such patent families. They are headed by Zimmer Biomet, which has 120 patent families linked via citations to Other DOE-funded patents. These Zimmer Biomet patents focus on prostheses, and methods of manufacturing these prostheses. They are linked to numerous earlier Other DOE-funded patents, notably the Sandia patents highlighted in the backward tracing element of the analysis (see Table 6). Apple is in second place in Figure 20 with 112 patent families, many of them related to electronic and lighting devices. These Apple families are linked particularly extensively to Other DOE-funded patents assigned to the University of Illinois describing foldable electronic devices (see for example US #8,552,299).

The third-placed company in Figure 21 is Midtronics, which specializes in battery and charger technology. It has 107 patent families linked via citations to earlier Other DOE-funded patents. These Midtronics patents concentrate primarily on battery monitors, and are linked to an earlier Oak Ridge National Laboratory patent (US #5,486,280) describing an electroforming method.

Figure 21 - Organizations with Largest Number of Patent Families Linked via Citations to Other DOE-funded Additive Manufacturing Patents (excluding leading additive manufacturing companies)



Patent Level Results

This section of the report drills down to identify individual DOE-funded additive manufacturing patents whose influence on subsequent technological developments has been particularly strong. It also highlights patents that have extensive citation links to earlier DOE-funded additive manufacturing research. The simplest way of identifying high-impact DOE-funded additive manufacturing patents is via overall Citation Indexes. The AMO-funded and Other DOE-funded patents with the highest Citation Index values are shown in Table 9, with selected patents also presented in Figure 22. The patents in this table are a mix of older patents that have been cited by numerous subsequent patents, and more recent patents that have attracted more citations than expected. One advantage of using Citation Indexes is that these two groups of patents can be compared directly, since each is benchmarked against patents of the same age and technology.

To date, there is only one AMO-funded additive manufacturing patent that has been cited as prior art by a series of subsequent patents. This patent (US #7,967,570) is shown at the head of Table 9. It is assigned to United Technologies and describes turbine component manufacturing. Since being issued in 2011, this patent has been cited as prior art by eight subsequent patents, slightly more citations than expected given its age and technology. It should be noted that some of these citations are from subsequent United Technologies patents, although this patent has also started to attract citations from other organizations.

Table 9 – List of Highly Cited DOE-Funded Additive Manufacturing Patents

Portfolio	Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
AMO	7967570	2011	8	1.21	United Technologies	Low transient thermal stress turbine engine components
Other DOE	8552299	2013	135	25.82	Univ Illinois	Stretchable and foldable electronic devices
Other DOE	7579112	2009	67	10.80	A123 Systems; MIT	Battery structures, self-organizing structures and related methods
Other DOE	5837960	1998	261	9.00	Univ California (LANL)	Laser production of articles from powders
Other DOE	6046426	2000	158	7.69	Sandia Corp (SNL)	Method and system for producing complex-shape objects
Other DOE	6993406	2006	143	5.97	Sandia Corp (SNL)	Method for making a bio-compatible scaffold
Other DOE	7556490	2009	36	4.55	Univ Texas	Multi-material stereolithography
Other DOE	5697043	1997	67	3.85	Battelle Memorial Inst (PNNL)	Method of freeform fabrication by selective gelation of powder suspensions
Other DOE	5718863	1998	40	2.41	Lockheed Martin (INL)	Spray forming process for producing molds, dies and related tooling

Figure 22 – Examples of Highly-Cited AMO-funded Additive Manufacturing Patents

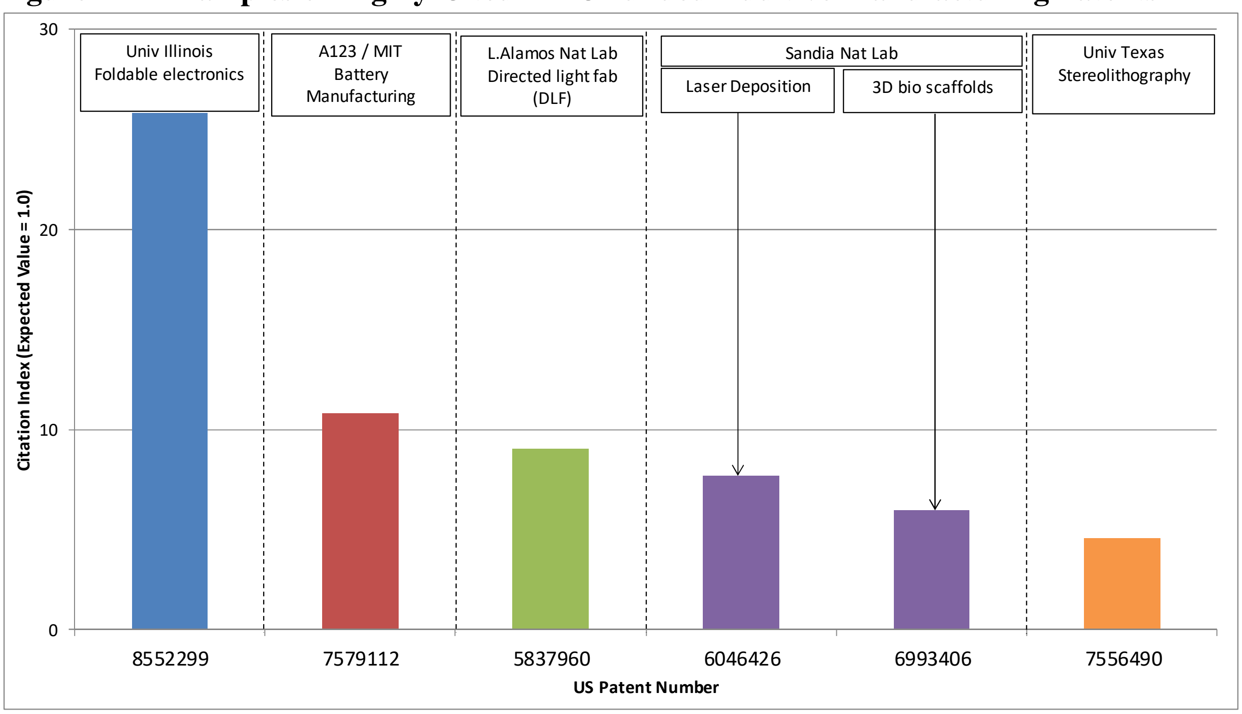


Table 9 also features a number of highly cited Other DOE-funded additive manufacturing patents. These are headed by a University of Illinois patent (US #8,552,299) describing foldable electronic devices. This patent was highlighted above in the discussion of Table 8. Since being issued in 2013, it has been cited as prior art by 135 subsequent patents, which is more than 25 times as many citations as expected for a patent of its age and technology. The next patent listed in Table 9 (US #7,579,112) is co-assigned to A123 Systems and Massachusetts Institute of Technology, and is related to battery manufacturing. It has been cited by 67 subsequent patents, more than ten times as many citations as expected. In terms of raw citation counts, the most highly cited patent is an older (1998) Los Alamos National Laboratory patent describing directed light fabrication. This patent, which was also highlighted in the backward tracing element of the analysis (see Table 6), has been cited by 261 subsequent patents, nine times as many as expected.

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

Table 10 contains DOE-funded patent families filed before 2005. All of these patent families are Other DOE-funded, rather than AMO-funded. The patent family at the head of this table contains the Los Alamos National Laboratory patent (US #5,837,960) that was the most highly-cited patent in Table 9. It was also highlighted in the backward tracing element of the analysis due to its extensive citation links to the leading additive manufacturing companies (see Table 6). This patent family outlines directed light fabrication. It is linked via citations to 1,575 subsequent patent families, 758 of which are from within additive manufacturing, with the remaining families related to a wide range of materials and manufacturing technologies.

The second patent family in Table 10 is one of a number of families in this table associated with Sandia National Laboratory. This family (representative patent US #6,046,426), which was highlighted in the backward tracing element of the analysis, describes production of objects via laser deposition of powders. This family is linked via citations to 856 subsequent patent families 368 of which are related to additive manufacturing, with many of the remaining families outlining advanced materials technologies. The third-place patent family in Table 10 (representative patent US #5,697,043) is assigned to Battelle Memorial Institute, the manager of Pacific Northwest National Laboratory. This patent family, which is linked to 612 subsequent families (377 from within additive manufacturing) outlines freeform fabrication of ceramics, and was also highlighted in the backward tracing.

Table 10 also contains patent families whose influence has been primarily outside additive manufacturing. For example, the A123/MIT patent family (representative patent US #7,579,112) is linked to 376 patent families, only nine of which are related to additive manufacturing, with most them describing battery technologies. Meanwhile, the Oak Ridge National Laboratory patent family (representative patent US #5,486,280) is also linked extensively to battery technologies, with all of the 284 families linked to it being from outside additive manufacturing.

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

Table 10 – Pre-2005 DOE-funded Additive Manufacturing Patent Families Linked via Citations to Largest Number of Subsequent Additive Manufacturing/Other Patent Families

Portfolio	Family #	Priority Year	Rep. Patent #	# Linked Fams	# Linked AM Fams	Assignee	Title
Other DOE	26670148	1995	5837960	1575	758	Univ California (LANL)	Laser production of articles from powders
Other DOE	24714964	1996	6046426	865	368	Sandia Corp (SNL)	Method and system for producing complex-shape objects
Other DOE	24618545	1996	5697043	612	377	Battelle Memorial Inst (PNNL)	Method of freeform fabrication by selective gelation of powder suspensions
Other DOE	25501511	1997	6027326	400	206	Sandia Corp (SNL)	Freeforming objects with low-binder slurry
Other DOE	26695046	2000	7579112	376	9	A123 Systems; MIT	Battery structures, self-organizing structures and related methods
Other DOE	23557912	1999	6348687	307	35	Sandia Corp (SNL)	Aerodynamic beam generator for large particles
Other DOE	23272147	1994	5486280	284	0	Lockheed Martin (ORNL)	Process for applying control variables having fractal structures
Other DOE	35694961	2003	6993406	253	65	Sandia Corp (SNL)	Method for making a bio-compatible scaffold
Other DOE	24260142	1995	5961862	245	46	Univ California (LANL)	Deposition head for laser
Other DOE	23557909	1999	6459951	239	133	Sandia Corp (SNL)	Direct laser additive fabrication system with image feedback control

Table 11 contains DOE-funded patent families filed since 2005. Most of these patent families are again Other DOE-funded, although there are two AMO-funded families in this table. The patent family at the head of this table stands out in terms of the number of subsequent families linked to it via citations. This family contains the patent (US #8,552,299) that had the highest Citation Index in Table 9. It is assigned to the University of Illinois and describes foldable electronic devices. In total, 471 subsequent patent families are linked to it via citations. Only five of these families are within additive manufacturing, with many of them describing electronics and display technologies.

The second patent family in Table 11 is linked to 100 patent families, 90 of which are related to additive manufacturing. This family (representative patent #7,419,630) is assigned to Sandia Corporation and describes rapid prototyping technology. Meanwhile, the two AMO-funded patent families in Table 11 are both towards the bottom of the table, with fewer than ten subsequent families linked to each of them. They are assigned to United Technologies and UT-Battelle (Oak Ridge National Laboratory), and describe turbine components and freeform fabrication respectively.

Table 11 – Post-2004 DOE-funded Additive Manufacturing Patent Families Linked via Citations to Largest Number of Subsequent Additive Manufacturing/Other Patent Families

Portfolio	Family #	Priority Year	Rep. Patent #	# Linked Fams	# Linked AM Fams	Assignee	Title
Other DOE	41056367	2008	8552299	471	5	Univ Illinois	Stretchable and foldable electronic devices
Other DOE	37186024	2005	7419630	100	90	Sandia Corp (SNL)	Methods and systems for rapid prototyping of high density circuits
Other DOE	43536270	2009	8181891	45	4	General Electric	Monolithic fuel injector and related manufacturing method
Other DOE	40584879	2005	7527671	19	10	Sandia Corp (SNL)	Regenerable particulate filter
Other DOE	37082045	2005	7658603	11	5	Univ Texas	Methods and systems for integrating fluid dispensing technology with stereolithography
Other DOE	37836313	2005	8064127	8	4	Princeton Univ	Quasicrystalline structures and uses thereof
AMO	39878497	2007	7967570	8	2	United Tech	Low transient thermal stress turbine engine components
Other DOE	41399197	2007	8256221	6	1	Siemens	Concentric tube support assembly
Other DOE	51210040	2013	9706646	6	0	Arizona St Univ, LLNL, Wayne St Univ	Origami enabled manufacturing systems and methods
AMO	49715918	2012	8951303	6	5	UT-Battelle (ORNL)	Freeform fluidics

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

The patent at the head of Table 12 (US #8,735,773) is assigned to Conformis, and describes the manufacture of patient-specific orthopedic implants. Since this patent was issued in 2014, it has been cited as prior art by 138 subsequent patents, which is more than 50 times as many citations as expected given its age and technology. The second patent in Table 12 (US #8,333,860) was issued in 2012 and assigned to LuxVue Technology, a company that was subsequently acquired by Apple. This patent outlines packaging and transfer of microscale devices. It has been cited as prior art by 132 subsequent patents, almost 30 times as many citations as expected. Semprius, a solar company that closed in 2017, was the original assignee on the patent in third place in Table 12. This patent (US #7,927,976), which has since been reassigned to X-Celeprint, describes composite stamps for printing semiconductor elements. This patent has been cited by 239 subsequent patents since it was issued in 2011, 27 times as many as expected. In general, Table 12 contains patents covering a wide range of materials and manufacturing applications, showing how the influence of DOE-funded additive manufacturing research has extended into other technologies.

Table 12 - Highly Cited Patents (not from leading additive manufacturing companies) Linked via Citations to Earlier AMO-funded Additive Manufacturing Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
8735773	2014	138	52.56	Conformis Inc	Implant device and method for manufacture
8333860	2012	132	29.08	Apple Inc	Method of transferring a micro device
7927976	2011	239	27.01	Semprius Inc	Reinforced composite stamp for dry transfer printing of semiconductor elements
7537664	2009	142	26.74	Stryker Corp.	Laser-produced porous surface
8389862	2013	103	19.70	MC10 Inc	Extremely stretchable electronics
6391251	2002	373	16.76	Optomec Design Co	Forming structures from CAD solid models
7625198	2009	93	15.28	Cornell University	Modular fabrication systems and methods
7261542	2007	117	12.53	Desktop Factory Inc	Apparatus for three dimensional printing using image layers
7204684	2007	103	11.03	Voxeljet AG	Interchangeable container

Overall, the forward tracing element of the analysis shows that DOE-funded additive manufacturing research (especially the more established Other DOE-funded research) has had a strong influence on subsequent technologies. This influence can be seen both within additive manufacturing and in other technologies, notably advanced materials, electronics and semiconductors, and medical devices.

5.0 Conclusions

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

The backward tracing element of the analysis shows that patents assigned to the leading additive manufacturing companies have strong citation links to earlier DOE-funded patents. Most of these citation links are to Other DOE-funded, rather than AMO-funded, patents. This reflects the fact that the Other DOE-funded additive manufacturing patent portfolio is much larger than the AMO-funded portfolio, and also contains older patents that have had a longer period over which to become linked to subsequent leading company innovations. Meanwhile, the forward tracing element of the analysis shows that DOE-funded additive manufacturing research (especially the more established Other DOE-funded research) has had a significant influence on subsequent technologies. This influence can be seen both within additive manufacturing and also in other technologies, notably advanced materials, electronics and semiconductors, and medical devices.

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

Appendix A. AMO-funded Additive Manufacturing Patents used in the Analysis

Patent #	Application Year	Issue / Publication Year	Assignee	Title
EP2025777	2008	2009	UNITED TECHNOLOGIES CORP	LOW TRANSIENT THERMAL STRESS TURBINE VANE
7958932	2008	2011	FOPAT LLC	CASTING MATERIALS
7967570	2007	2011	UNITED TECHNOLOGIES CORP	LOW TRANSIENT THERMAL STRESS TURBINE ENGINE COMPONENTS
8210420	2011	2012	UT-BATTELLE LLC	COMPOSITE BIAXIALLY TEXTURED SUBSTRATES USING ULTRASONIC CONSOLIDATION
WO2012106196	2012	2012	UT-BATTELLE LLC	COMPOSITE BIAXIALLY TEXTURED SUBSTRATES USING ULTRASONIC CONSOLIDATION
8424745	2012	2013	UT-BATTELLE LLC	COMPOSITE BIAXIALLY TEXTURED SUBSTRATES USING ULTRASONIC CONSOLIDATION
8591787	2011	2013	IC PATTERNS LLC	FOAM PATTERNS
8951303	2012	2015	UT-BATTELLE LLC	FREEFORM FLUIDICS
9499406	2015	2016	CONSOLIDATED NUCLEAR SECURITY LLC	METHODS FOR THE ADDITIVE MANUFACTURING OF SEMICONDUCTOR AND CRYSTAL MATERIALS
WO2016073065	2015	2016	UT-BATTELLE LLC	METHOD OF FORMING A CARBON FIBER LAYUP
WO2016168142	2016	2016	UT-BATTELLE LLC	LOW SHEAR PROCESS FOR PRODUCING POLYMER COMPOSITE FIBERS
9650537	2014	2017	UT-BATTELLE LLC	REACTIVE POLYMER FUSED DEPOSITION MANUFACTURING
9821502	2015	2017	UT-BATTELLE LLC	MULTI-ORIFICE DEPOSITION NOZZLE FOR ADDITIVE MANUFACTURING
9884444	2014	2018	UT-BATTELLE LLC	ENHANCED ADDITIVE MANUFACTURING WITH A RECIPROCATING PLATEN
9908287	2014	2018	UT-BATTELLE LLC	BUILD PLATFORM THAT PROVIDES MECHANICAL ENGAGEMENT WITH ADDITIVE MANUFACTURING PRINTS
10093067	2014	2018	UT-BATTELLE LLC	METHOD OF FORMING A CARBON FIBER LAYUP
10105876	2015	2018	UT-BATTELLE LLC	APPARATUS FOR GENERATING AND DISPENSING A POWDERED RELEASE AGENT

10124531	2013	2018	UT-BATTELLE LLC	RAPID NON-CONTACT ENERGY TRANSFER FOR ADDITIVE MANUFACTURING DRIVEN HIGH INTENSITY ELECTROMAGNETIC FIELDS
10137617	2015	2018	UT-BATTELLE LLC	LOW SHEAR PROCESS FOR PRODUCING POLYMER COMPOSITE FIBERS
10245781	2018	2019	UT-BATTELLE LLC	METHOD FOR PRODUCING MECHANICAL ENGAGEMENT BETWEEN A BUILD PLATFORM AND ADDITIVE MANUFACTURING PRINTS

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

Patent #	Application Year	Issue / Publication Year	Assignee	Title
5486280	1994	1996	MARTIN MARIETTA ENERGY SYSTEMS INC	PROCESS FOR APPLYING CONTROL VARIABLES HAVING FRACTAL STRUCTURES
5697043	1996	1997	BATTELLE MEMORIAL INSTITUTE	METHOD OF FREEFORM FABRICATION BY SELECTIVE GELATION OF POWDER SUSPENSIONS
WO1997021515	1996	1997	UNIVERSITY OF CALIFORNIA	DEPOSITION HEAD FOR PRODUCTION OF ARTICLES FROM POWDERS
WO1997044291	1997	1997	BATTELLE MEMORIAL INSTITUTE	METHOD OF FREEFORM FABRICATION BY SELECTIVE GELATION OF POWDER SUSPENSIONS
5718863	1994	1998	LOCKHEED IDAHO TECHNOLOGIES CO	SPRAY FORMING PROCESS FOR PRODUCING MOLDS, DIES AND RELATED TOOLING
5837960	1995	1998	UNIVERSITY OF CALIFORNIA	LASER PRODUCTION OF ARTICLES FROM POWDERS
5847283	1996	1998	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	METHOD AND APPARATUS FOR THE EVALUATION OF A DEPTH PROFILE OF THERMO-MECHANICAL PROPERTIES OF LAYERED AND GRADED MATERIALS AND COATINGS
WO1998000698	1997	1998	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	METHOD AND APPARATUS FOR THE EVALUATION OF A DEPTH PROFILE OF THERMO-MECHANICAL PROPERTIES OF LAYERED AND GRADED MATERIALS AND COATINGS
5961862	1995	1999	UNIVERSITY OF CALIFORNIA	DEPOSITION HEAD FOR LASER
5975493	1997	1999	UNIVERSITY OF CHICAGO	PROCESS FOR CONTROLLING FLOW RATE OF VISCOUS MATERIALS INCLUDING USE OF A NOZZLE WITH CHANGEABLE OPENING
6027326	1997	2000	SANDIA CORP	FREEFORMING OBJECTS WITH LOW-BINDER SLURRY
6027699	1997	2000	LOCKHEED MARTIN ENERGY RESEARCH CORP	MATERIAL FORMING APPARATUS USING A DIRECTED DROPLET STREAM
6046426	1996	2000	SANDIA CORP	METHOD AND SYSTEM

				FOR PRODUCING COMPLEX-SHAPE OBJECTS
6074194	1998	2000	BECHTEL BWXT IDAHO LLC	SPRAY FORMING SYSTEM FOR PRODUCING MOLDS, DIES AND RELATED TOOLING
6080343	1997	2000	SANDIA CORP	METHODS FOR FREEFORM FABRICATION OF STRUCTURES
6107008	1997	2000	LOCKHEED MARTIN ENERGY RESEARCH CORP	IONIZING RADIATION POST-CURING OF OBJECTS PRODUCED BY STEREOLITHOGRAPHY AND OTHER METHODS
6143378	1998	2000	SANDIA CORP	ENERGETIC ADDITIVE MANUFACTURING PROCESS WITH FEED WIRE
6202734	1998	2001	SANDIA CORP	APPARATUS FOR JET APPLICATION OF MOLTEN METAL DROPLETS FOR MANUFACTURE OF METAL PARTS
WO2001091965	2001	2001	UNIVERSITY OF CALIFORNIA	CONTROLLED LASER PRODUCTION OF ELONGATED ARTICLES FROM PARTICULATES
WO2001096049	2001	2001	BECHTEL BWXT IDAHO LLC	RAPID SOLIDIFICATION PROCESSING SYSTEM FOR PRODUCING MOLDS, DIES AND RELATED TOOLING
6348687	1999	2002	SANDIA CORP	AERODYNAMIC BEAM GENERATOR FOR LARGE PARTICLES
6401795	2000	2002	SANDIA CORP	METHOD FOR FREEFORMING OBJECTS WITH LOW-BINDER SLURRY
6429402	2000	2002	UNIVERSITY OF CALIFORNIA	CONTROLLED LASER PRODUCTION OF ELONGATED ARTICLES FROM PARTICULATES
6454972	2000	2002	SANDIA CORP	SOLID FREEFORM FABRICATION USING CHEMICALLY REACTIVE SUSPENSIONS
6459951	1999	2002	SANDIA CORP	DIRECT LASER ADDITIVE FABRICATION SYSTEM WITH IMAGE FEEDBACK CONTROL
6476343	1998	2002	SANDIA CORP	ENERGY-BEAM-DRIVEN RAPID FABRICATION SYSTEM
EP1289699	2001	2003	BECHTEL BWXT IDAHO LLC	RAPID SOLIDIFICATION PROCESSING SYSTEM FOR PRODUCING MOLDS, DIES AND RELATED TOOLING

WO2003012908	2002	2003	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	BATTERY STRUCTURES, SELF-ORGANIZING STRUCTURES AND RELATED METHODS
WO2003047828	2002	2003	ADVANCED CERAMICS RESEARCH INC	METHOD FOR PREPARATION OF THREE-DEMENSIONAL BODIES
6746225	2000	2004	BECHTEL BWXT IDAHO LLC	RAPID SOLIDIFICATION PROCESSING SYSTEM FOR PRODUCING MOLDS, DIES AND RELATED TOOLING
6797220	2001	2004	ADVANCED CERAMICS RESEARCH INC	METHODS FOR PREPARATION OF THREE-DIMENSIONAL BODIES
EP1433217	2002	2004	A123 SYSTEMS INC, MASSACHUSETTS INSTITUTE OF TECHNOLOGY	BATTERY STRUCTURES, SELF-ORGANIZING STRUCTURES AND RELATED METHODS
WO2005000977	2004	2005	UNIVERSITY OF ILLINOIS	DIRECTED ASSEMBLY OF THREE-DIMENSIONAL STRUCTURES WITH MICRON-SCALE FEATURES
WO2005019852	2004	2005	BATTELLE MEMORIAL INSTITUTE	SLOW-MAGIC ANGLE SPINNING PROBE FOR MAGNETIC RESONANCE IMAGING AND SPECTROSCOPY
6989674	2003	2006	BATTELLE MEMORIAL INSTITUTE	ADVANCED SLOW-MAGIC ANGLE SPINNING PROBE FOR MAGNETIC RESONANCE IMAGING AND SPECTROSCOPY
6993406	2004	2006	SANDIA CORP	METHOD FOR MAKING A BIO-COMPATIBLE SCAFFOLD
7141617	2003	2006	UNIVERSITY OF ILLINOIS	DIRECTED ASSEMBLY OF THREE-DIMENSIONAL STRUCTURES WITH MICRON-SCALE FEATURES
WO2006091653	2006	2006	UNIVERSITY OF CALIFORNIA	FLEXIBLE HYDROGEL-BASED FUNCTIONAL COMPOSITE MATERIALS
EP1851268	2006	2007	UNIVERSITY OF CALIFORNIA	FLEXIBLE HYDROGEL-BASED FUNCTIONAL COMPOSITE MATERIALS
WO2007030196	2006	2007	PRINCETON UNIVERSITY	QUASICRYSTALLINE STRUCTURES AND USES THEREOF
7387757	2004	2008	ADVANCED CERAMICS RESEARCH INC	METHODS FOR PREPARATION OF THREE-DIMENSIONAL BODIES
7411361	2006	2008	RADIABEAM TECHNOLOGIES LLC	METHOD AND APPARATUS FOR RADIO FREQUENCY CAVITY
7419630	2005	2008	SANDIA CORP	METHODS AND SYSTEMS FOR RAPID PROTOTYPING

				OF HIGH DENSITY CIRCUITS
EP1910875	2006	2008	PRINCETON UNIVERSITY	QUASICRYSTALLINE STRUCTURES AND USES THEREOF
7527671	2006	2009	SANDIA CORP	REGENERABLE PARTICULATE FILTER
7556490	2004	2009	UNIVERSITY OF TEXAS	MULTI-MATERIAL STEREOLITHOGRAPHY
7579112	2002	2009	A123 SYSTEMS INC, MASSACHUSETTS INSTITUTE OF TECHNOLOGY	BATTERY STRUCTURES, SELF-ORGANIZING STRUCTURES AND RELATED METHODS
WO2009111641	2009	2009	UNIVERSITY OF ILLINOIS	STRETCHABLE AND FOLDABLE ELECTRONIC DEVICES
7658603	2005	2010	UNIVERSITY OF TEXAS, SANDIA CORP	METHODS AND SYSTEMS FOR INTEGRATING FLUID DISPENSING TECHNOLOGY WITH STEREOLITHOGRAPHY
7790061	2006	2010	UNIVERSITY OF ILLINOIS	DIRECTED ASSEMBLY OF THREE-DIMENSIONAL STRUCTURES WITH MICRON-SCALE FEATURES
EP2255378	2009	2010	UNIVERSITY OF ILLINOIS	STRETCHABLE AND FOLDABLE ELECTRONIC DEVICES
7908970	2007	2011	SANDIA CORP	DUAL INITIATION STRIP CHARGE APPARATUS AND METHODS FOR MAKING AND IMPLEMENTING THE SAME
7959847	2009	2011	UNIVERSITY OF TEXAS	METHODS FOR MULTI-MATERIAL STEREOLITHOGRAPHY
7988746	2010	2011	A123 SYSTEMS INC, MASSACHUSETTS INSTITUTE OF TECHNOLOGY	BATTERY STRUCTURES, SELF-ORGANIZING STRUCTURES AND RELATED METHODS
8064127	2006	2011	PRINCETON UNIVERSITY	QUASICRYSTALLINE STRUCTURES AND USES THEREOF
8157948	2008	2012	LOS ALAMOS NATIONAL SECURITY LLC	METHOD OF FABRICATING METAL- AND CERAMIC-MATRIX COMPOSITES AND FUNCTIONALIZED TEXTILES
8168326	2009	2012	A123 SYSTEMS INC, MASSACHUSETTS INSTITUTE OF TECHNOLOGY	BATTERY STRUCTURES, SELF-ORGANIZING STRUCTURES AND RELATED METHODS
8181891	2009	2012	GENERAL ELECTRIC CO	MONOLITHIC FUEL INJECTOR AND RELATED MANUFACTURING METHOD

8206468	2010	2012	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	BATTERY STRUCTURES, SELF-ORGANIZING STRUCTURES AND RELATED METHODS
8206469	2011	2012	A123 SYSTEMS INC, MASSACHUSETTS INSTITUTE OF TECHNOLOGY	BATTERY STRUCTURES, SELF-ORGANIZING STRUCTURES AND RELATED METHODS
8241789	2010	2012	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	BATTERY STRUCTURES, SELF-ORGANIZING STRUCTURES AND RELATED METHODS
8243362	2011	2012	PRINCETON UNIVERSITY	QUASICRYSTALLINE STRUCTURES AND USES THEREOF
8252223	2009	2012	UNIVERSITY OF TEXAS, SANDIA CORP	METHODS AND SYSTEMS FOR INTEGRATING FLUID DISPENSING TECHNOLOGY WITH STEREOLITHOGRAPHY
8256221	2007	2012	SIEMENS ENERGY INC	CONCENTRIC TUBE SUPPORT ASSEMBLY
8291705	2008	2012	GENERAL ELECTRIC CO	ULTRA LOW INJECTION ANGLE FUEL HOLES IN A COMBUSTOR FUEL NOZZLE
WO2012064972	2011	2012	STC UNM	AEROSOL REDUCTION/EXPANSION SYNTHESIS (A-RES) FOR ZERO VALENT METAL PARTICLES
8508838	2012	2013	PRINCETON UNIVERSITY	QUASICRYSTALLINE STRUCTURES AND USES THEREOF
8552100	2006	2013	UNIVERSITY OF CALIFORNIA	FLEXIBLE HYDROGEL-BASED FUNCTIONAL COMPOSITE MATERIALS
8552299	2009	2013	UNIVERSITY OF ILLINOIS	STRETCHABLE AND FOLDABLE ELECTRONIC DEVICES
8580430	2012	2013	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	BATTERY STRUCTURES, SELF-ORGANIZING STRUCTURES, AND RELATED METHODS
8586238	2012	2013	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	BATTERY STRUCTURES, SELF-ORGANIZING STRUCTURES, AND RELATED METHODS
8599472	2013	2013	PRINCETON UNIVERSITY	QUASICRYSTALLINE STRUCTURES AND USES THEREOF
EP2637816	2011	2013	STC UNM	AEROSOL REDUCTION/EXPANSION SYNTHESIS (A-RES) FOR ZERO VALENT METAL PARTICLES

8837672	2012	2014	SAVANNAH RIVER NUCLEAR SOLUTIONS LLC	CONCEALED IDENTIFICATION SYMBOLS AND NONDESTRUCTIVE DETERMINATION OF THE IDENTIFICATION SYMBOLS
8905772	2013	2014	UNIVERSITY OF ILLINOIS, NORTHWESTERN UNIVERSITY	STRETCHABLE AND FOLDABLE ELECTRONIC DEVICES
WO2014113489	2014	2014	ARIZONA STATE UNIVERSITY, LAWRENCE LIVERMORE NATIONAL SECURITY LLC, WAYNE STATE UNIVERSITY	ORIGAMI ENABLED MANUFACTURING SYSTEMS AND METHODS
WO2014138192	2014	2014	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	SYSTEM AND METHOD FOR HIGH POWER DIODE BASED ADDITIVE MANUFACTURING
WO2014193984	2014	2014	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	THREE-DIMENSIONALLY PATTERNED ENERGY ABSORPTIVE MATERIAL AND METHOD OF FABRICATION
9023765	2014	2015	JEFFERSON SCIENCE ASSOCIATES LLC	ADDITIVE MANUFACTURING METHOD FOR SRF COMPONENTS OF VARIOUS GEOMETRIES
9278465	2014	2016	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	SYSTEM AND METHOD FOR 3D PRINTING OF AEROGELS
9308583	2013	2016	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	SYSTEM AND METHOD FOR HIGH POWER DIODE BASED ADDITIVE MANUFACTURING
9308585	2011	2016	STC UNM	AEROSOL REDUCTION/EXPANSION SYNTHESIS (A-RES) FOR ZERO VALENT METAL PARTICLES
9309809	2013	2016	GENERAL ELECTRIC CO	EFFUSION PLATE USING ADDITIVE MANUFACTURING METHODS
9373923	2012	2016	SAVANNAH RIVER NUCLEAR SOLUTIONS LLC	RAPID PROTOTYPE EXTRUDED CONDUCTIVE PATHWAYS
9453289	2011	2016	LAWRENCE LIVERMORE NATIONAL	METHODS OF THREE-DIMENSIONAL ELECTROPHORETIC

			SECURITY LLC	DEPOSITION FOR CERAMIC AND CERMET APPLICATIONS AND SYSTEMS THEREOF
9492969	2011	2016	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	HIGH RESOLUTION PROJECTION MICRO STEREOLITHOGRAPHY SYSTEM AND METHOD
EP2963675	2009	2016	UNIVERSITY OF ILLINOIS, NORTHWESTERN UNIVERSITY	STRETCHABLE AND FOLDABLE ELECTRONIC DEVICES
EP2964418	2014	2016	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	SYSTEM AND METHOD FOR HIGH POWER DIODE BASED ADDITIVE MANUFACTURING
EP3034206	2015	2016	GENERAL ELECTRIC CO	HYBRID ADDITIVE MANUFACTURING METHOD FOR FORMING HYBRID ADDITIVELY MANUFACTURED FEATURES FOR HYBRID COMPONENT
EP3040522	2015	2016	GENERAL ELECTRIC CO	HOT GAS PATH COMPONENT AND METHODS OF MANUFACTURE
EP3081323	2016	2016	GENERAL ELECTRIC CO	ARTICLE WITH COOLING CHANNELS AND MANUFACTURING METHOD THEREOF
EP3098386	2016	2016	GENERAL ELECTRIC CO	IMPINGEMENT INSERT
WO2016089838	2015	2016	SAVANNAH RIVER NUCLEAR SOLUTIONS LLC	ADDITIVE MANUFACTURED SERIALIZATION
WO2016164562	2016	2016	PRESIDENT & FELLOWS OF HARVARD COLLEGE	MICROFLUIDIC ACTIVE MIXING NOZZLE FOR THREE-DIMENSIONAL PRINTING OF VISCOELASTIC INKS
9555583	2013	2017	SANDIA CORP, STC UNM	FABRICATION OF NEURAL INTERFACES USING 3D PROJECTION MICRO-STEREOLITHOGRAPHY
9567420	2013	2017	PRINCETON UNIVERSITY	QUASICRYSTALLINE STRUCTURES AND USES THEREOF
9611745	2014	2017	FLORIDA TURBINE TECHNOLOGIES INC	SEQUENTIAL COOLING INSERT FOR TURBINE STATOR VANE
9626608	2015	2017	SAVANNAH RIVER NUCLEAR SOLUTIONS LLC	ADDITIVE MANUFACTURED SERIALIZATION
9706646	2014	2017	ARIZONA STATE UNIVERSITY,	ORIGAMI ENABLED MANUFACTURING

			LAWRENCE LIVERMORE NATIONAL SECURITY LLC, WAYNE STATE UNIVERSITY	SYSTEMS AND METHODS
9707716	2014	2017	UCHICAGO ARGONNE LLC	SELF-ASSEMBLED TUNABLE NETWORKS OF STICKY COLLOIDAL PARTICLES
9708451	2014	2017	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	SILICONE ELASTOMERS CAPABLE OF LARGE ISOTROPIC DIMENSIONAL CHANGE
9744476	2016	2017	UCHICAGO ARGONNE LLC	3D PRINTED MODULAR CENTRIFUGAL CONTACTORS AND METHOD FOR SEPARATING MOIETIES USING 3D PRINTED OPTIMIZED SURFACES
9757936	2014	2017	GENERAL ELECTRIC CO	HOT GAS PATH COMPONENT
9796048	2014	2017	GENERAL ELECTRIC CO	ARTICLE AND PROCESS FOR PRODUCING AN ARTICLE
9833837	2014	2017	IOWA STATE UNIVERSITY	PASSIVATION AND ALLOYING ELEMENT RETENTION IN GAS ATOMIZED POWDERS
9849510	2015	2017	GENERAL ELECTRIC CO	ARTICLE AND METHOD OF FORMING AN ARTICLE
EP3168419	2016	2017	GENERAL ELECTRIC CO	ARTICLE AND METHOD OF FORMING AN ARTICLE
EP3236093	2017	2017	GENERAL ELECTRIC CO	THRUST AIR BEARING
WO2017147108	2017	2017	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	ARCHITECTED MATERIALS AND STRUCTURES TO CONTROL SHOCK OUTPUT CHARACTERISTICS
9855625	2016	2018	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	SYSTEM AND METHOD FOR HIGH POWER DIODE BASED ADDITIVE MANUFACTURING
9862140	2015	2018	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	ADDITIVE MANUFACTURING OF SHORT AND MIXED FIBRE-REINFORCED POLYMER
9890092	2017	2018	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	EXPLOSIVES MIMIC FOR TESTING, TRAINING, AND MONITORING
9897419	2017	2018	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	K-9 TRAINING AIDS MADE USING ADDITIVE MANUFACTURING

9908823	2015	2018	BATTELLE ENERGY ALLIANCE LLC	FLEXIBLE ENERGETIC MATERIALS AND RELATED METHODS
9931695	2014	2018	GENERAL ELECTRIC CO	ARTICLE AND METHOD FOR MAKING AN ARTICLE
9931814	2014	2018	GENERAL ELECTRIC CO	ARTICLE AND METHOD FOR MAKING AN ARTICLE
9944016	2015	2018	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	HIGH PERFORMANCE, RAPID THERMAL/UV CURING EPOXY RESIN FOR ADDITIVE MANUFACTURING OF SHORT AND CONTINUOUS CARBON FIBER EPOXY COMPOSITES
9962905	2013	2018	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	THREE-DIMENSIONALLY PATTERNED ENERGY ABSORPTIVE MATERIAL AND METHOD OF FABRICATION
9976441	2015	2018	GENERAL ELECTRIC CO	ARTICLE, COMPONENT, AND METHOD OF FORMING AN ARTICLE
10003059	2015	2018	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	ION CONDUCTIVE INKS AND SOLUTIONS FOR ADDITIVE MANUFACTURING OF LITHIUM MICROBATTERIES
10036279	2016	2018	GENERAL ELECTRIC CO	THRUST BEARING
10036616	2016	2018	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	ARCHITECTED MATERIALS AND STRUCTURES TO CONTROL SHOCK OUTPUT CHARACTERISTICS
10041171	2015	2018	DELAVAN INC	PARTICULATES FOR ADDITIVE MANUFACTURING TECHNIQUES
10058881	2017	2018	NATIONAL TECHNOLOGY & ENGINEERING SOLUTIONS OF SANDIA LLC	APPARATUS FOR PNEUMATIC SHUTTERING OF AN AEROSOL PARTICLE STREAM
10064269	2014	2018	UNIVERSITY OF ILLINOIS	STRETCHABLE AND FOLDABLE ELECTRONIC DEVICES
10071350	2016	2018	PRESIDENT & FELLOWS OF HARVARD COLLEGE	MICROFLUIDIC ACTIVE MIXING NOZZLE FOR THREE-DIMENSIONAL PRINTING OF VISCOELASTIC INKS
10085348	2016	2018	SAVANNAH RIVER NUCLEAR SOLUTIONS LLC	RAPID PROTOTYPE EXTRUDED CONDUCTIVE PATHWAYS
10087776	2015	2018	GENERAL ELECTRIC	ARTICLE AND METHOD OF

			CO	FORMING AN ARTICLE
10099290	2014	2018	GENERAL ELECTRIC CO	HYBRID ADDITIVE MANUFACTURING METHODS USING HYBRID ADDITIVELY MANUFACTURED FEATURES FOR HYBRID COMPONENTS
10118338	2015	2018	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	ADDITIVE MANUFACTURING WITH INTEGRATED MICROLITER RESIN DELIVERY
10130961	2015	2018	NATIONAL TECHNOLOGY & ENGINEERING SOLUTIONS OF SANDIA LLC	TWO-FLUID HYDRODYNAMIC PRINTING
10138330	2017	2018	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	SILICONE ELASTOMERS CAPABLE OF LARGE ISOTROPIC DIMENSIONAL CHANGE
10246539	2017	2019	PRINCETON UNIVERSITY	QUASICRYSTALLINE STRUCTURES AND USES THEREOF
10292261	2015	2019	UNIVERSITY OF ILLINOIS, NORTHWESTERN UNIVERSITY	STRETCHABLE AND FOLDABLE ELECTRONIC DEVICES
10322575	2017	2019	GENERAL ELECTRIC CO	HOT GAS PATH COMPONENT AND METHODS OF MANUFACTURE
10407792	2016	2019	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	METHODS OF THREE-DIMENSIONAL ELECTROPHORETIC DEPOSITION FOR CERAMIC AND CERMET APPLICATIONS AND SYSTEMS THEREOF
10464031	2018	2019	PRESIDENT & FELLOWS OF HARVARD COLLEGE	MICROFLUIDIC ACTIVE MIXING NOZZLE FOR THREE-DIMENSIONAL PRINTING OF VISCOELASTIC INKS
10533261	2016	2020	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	METHODS OF THREE-DIMENSIONAL ELECTROPHORETIC DEPOSITION FOR CERAMIC AND CERMET APPLICATIONS AND SYSTEMS THEREOF

An Analysis of the Influence of AMO-funded Additive Manufacturing Patents

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