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ADVANCED MATERIALS & MANUFACTURING TECHNOLOGIES OFFICE

An Evaluation of the Patent Portfolio Funded by the U.S. Department of Energy's Critical Materials Innovation Hub

Report prepared for:

U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Critical Materials Innovation Hub

Ames National Laboratory
Ames, Iowa

Report prepared by:

1790 Analytics LLC
130 North Haddon Avenue
Haddonfield, NJ 08033

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1790 ANALYTICS

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Executive Summary

This report describes the results of an analysis of critical materials research funded by the U.S. Department of Energy (DOE) Critical Materials Innovation Hub (CMI Hub, formerly the Critical Materials Institute). The purpose of the report is to assess various characteristics of patents awarded for CMI Hub-funded innovations in critical materials technology; and to determine the extent to which CMI Hub-funded research has influenced subsequent technological developments both within and beyond critical materials.

The analysis presented in this report 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 the analysis is 2012 (the year that the first CMI Hub-funded patent family was filed) to June 2023.

Findings

The main finding of this report is CMI Hub funding has resulted in patents across a range of critical materials technologies—including metals recycling, recovery of lithium and rare earth materials, and advanced aluminum alloys—and this funding may be helping to fill research gaps not addressed by the leading companies. Although many of the CMI Hub-funded patents are relatively recent, there are already numerous examples of their influence on downstream innovations, both within critical materials and in other technologies, notably additive manufacturing.

More detailed findings from this report include:

- In critical materials technology, in the period 2012-June 2023, there were a total of 13,623 patents across the three patent systems included in the analysis (3,727 EPO patents, 3,511 U.S. patents, and 6,385 WIPO patents). These patents are grouped into 8,022 patent families, where each family contains all patents resulting from the same initial application (named the priority application).
- 57 critical materials patents are confirmed to be associated with CMI Hub funding (42 U.S. patents and 15 WIPO patents). These CMI Hub-funded critical materials patents are grouped into 34 patent families. They represent 0.4% of all critical materials patent families filed between 2012 and June 2023.
- Figure E-1 shows the number of CMI Hub-funded granted U.S. patents by issue year (i.e., the year in which they were granted). The first CMI Hub-funded U.S. patent was granted in 2016, and thereafter the number of patents by year increased steadily, peaking at nine granted U.S. patents in 2020. After that time, the number of CMI Hub-funded U.S. patents declined slightly to six in 2021 and seven in 2022. Figure E-1 shows five CMI Hub-funded U.S. patents in 2023, but it should be noted that this is only for the first 6 months of the year. It may be that the final number of CMI Hub-funded U.S. patents shows an increase in 2023 once the year is complete.
- UT-Battelle is the most prolific assignee of CMI Hub-funded patents, with 19 families resulting from its management of Oak Ridge National Laboratory. It is followed by two other DOE lab managers—Iowa State University (Ames National Laboratory) with 13 CMI Hub-funded patent families, and Lawrence Livermore National Security (Lawrence Livermore National Laboratory) with seven families. There are also three companies with at least two CMI Hub-funded patent families: Eck Industries (6), General Electric (2) and TerraLithium (2), with the latter patent families originally assigned to All American Lithium and Alger Alternative Energy. It should be

noted that a number of CMI Hub-funded patent families are co-assigned to multiple organizations in this list.

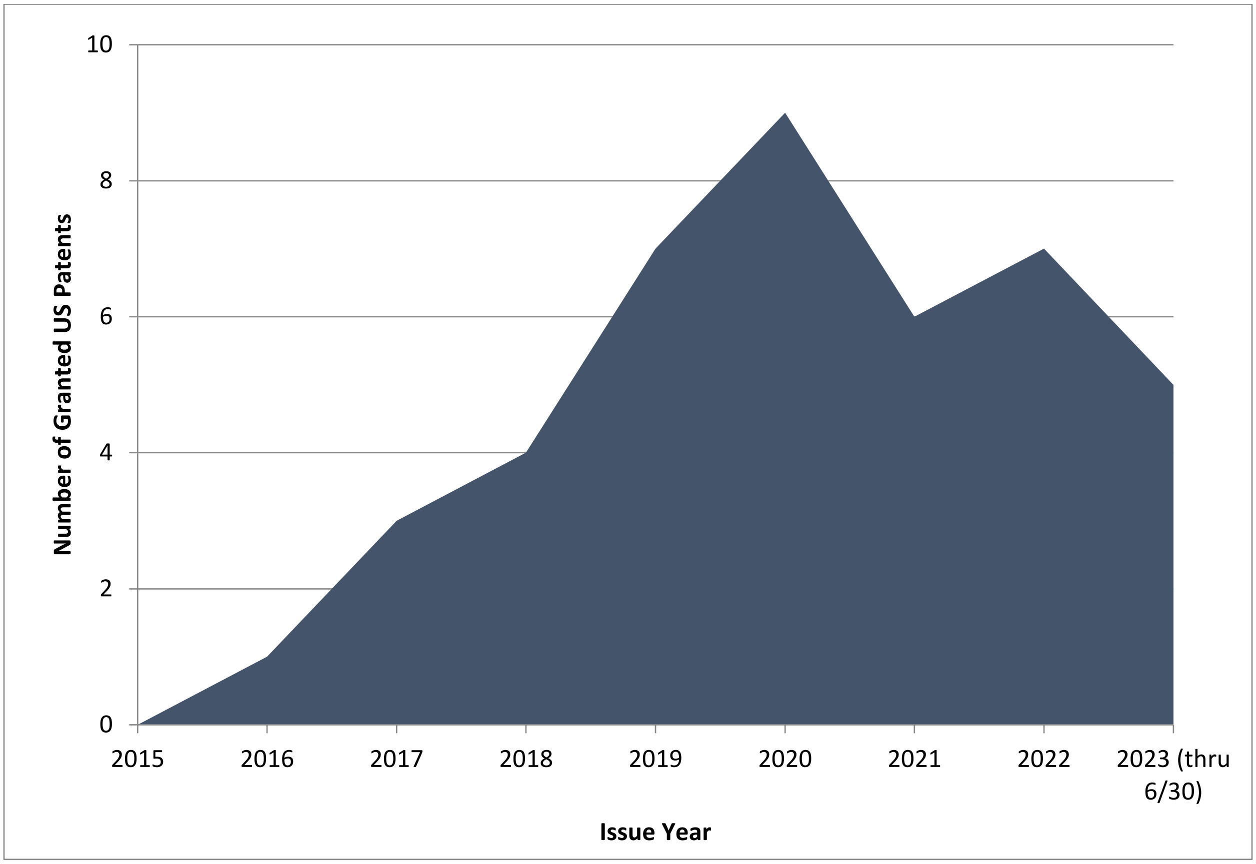

Figure E-1. Number of CMI Hub-funded U.S. patents granted by issue year

- The 10 companies with the largest critical materials patent portfolios between 2012 and June 2023 are: POSCO (193 patent families); Sumitomo Metal Mining (183); General Electric (96); Sumitomo Electric (96); Toyota (88); Siemens (82); Panasonic (79); Raytheon (73); Umicore (68); and BASF (65). The portfolio of 34 CMI Hub-funded critical materials patent families is smaller than those assigned to the leading companies but is in a similar region to most of them in terms of scale, other than POSCO and Sumitomo Metal Mining.
- CMI Hub-funded critical materials patents have a particular focus on recycling metals, lithium recovery, and aluminum alloys containing critical materials. The leading companies, and critical materials patents overall, also have a notable presence in recycling metals. They have a lesser focus on lithium recovery and aluminum alloys (their patents being directed more towards ferrous alloys containing critical materials). This suggests that CMI Hub-funded critical materials research may be helping to fill a research gap not addressed extensively by the leading companies.
- Tracing forwards through two generations of citations to CMI Hub-funded patents reveals the influence of these patents on subsequent developments both within and outside critical materials technology. There are 68 patent families linked via citations to earlier CMI Hub-funded patents

(not including 11 cases where CMI Hub-funded families are linked via citations to earlier CMI Hub-funded patents).

- The influence of CMI Hub-funded patents on subsequent developments can be seen in critical materials technologies such as metals recycling, lithium recovery and advanced aluminum alloys. Their influence can also be detected beyond critical materials, notably in additive manufacturing with specific applications as varied as printing systems, vehicle components, and contact lenses.
- There are a number of individual CMI Hub-funded patent families linked via citations to numerous subsequent patent families, examples of which are shown in Figure E-2. They include CMI Hub-funded patent families for three-dimensionally printed liquid crystal elastomers, lithium recovery from brines, additive manufacturing of molten metals, advanced aluminum alloys containing critical materials, recycling of metals from electronic waste, and recycling of rare earth magnets. These CMI Hub-funded patent families result from CMI Hub focus areas, such as diversifying supply and driving reuse and recycling.

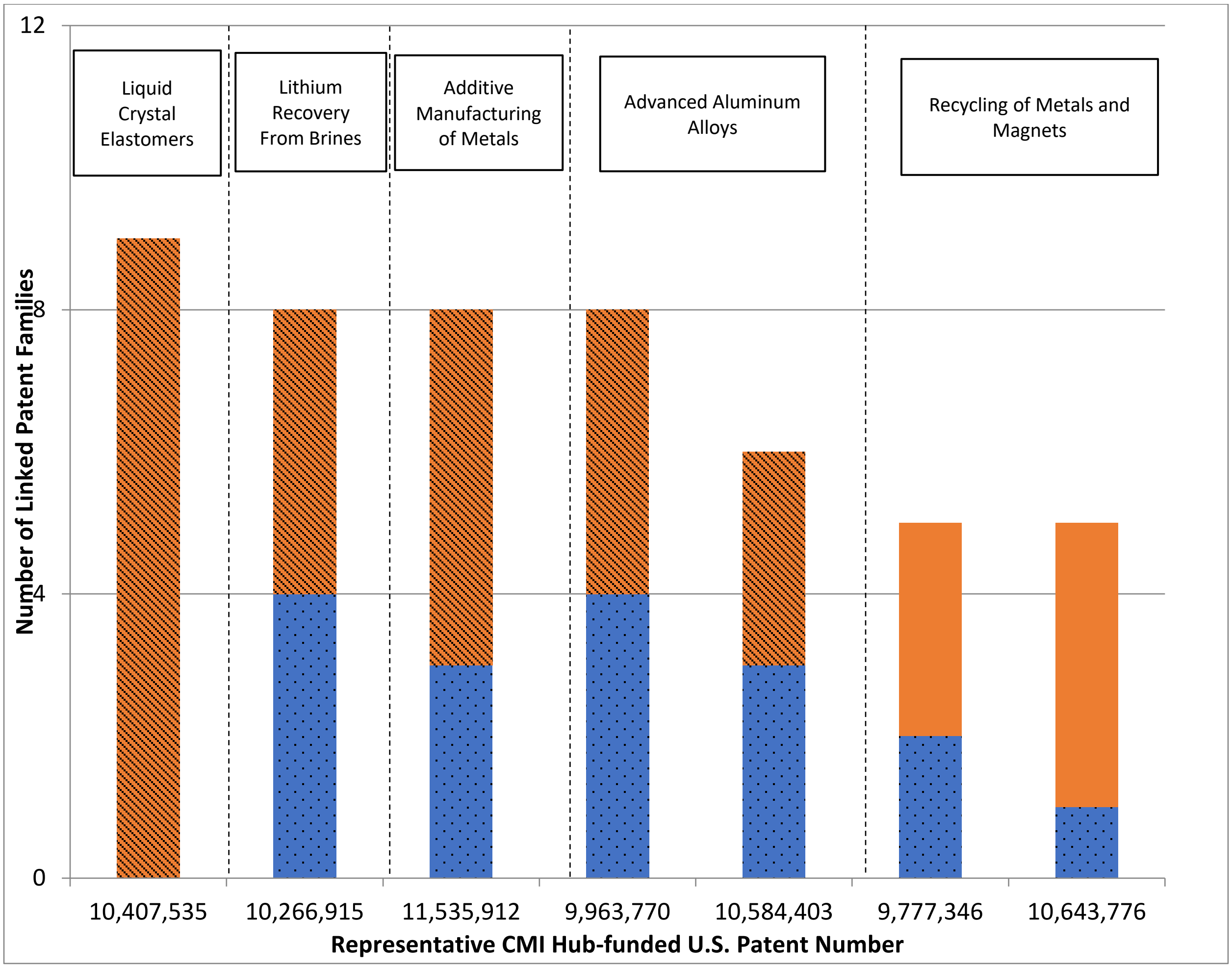

Figure E-2. Examples of highly-linked CMI Hub-funded critical materials patent families (with blue dotted=citations from critical materials patent families and orange hashed=citations from other families)

1 Introduction

This report provides an evaluation of critical materials research funded by the U.S. Department of Energy (DOE) Critical Materials Innovation Hub (CMI Hub). The purpose of the report is to assess various characteristics of patents awarded for CMI Hub-funded inventions in critical materials technology; and to determine the extent to which CMI Hub-funded research has influenced subsequent technological developments both within and beyond critical materials.

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 multigeneration 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 datasets were constructed and linked.

The third section presents the results of our analysis. Results are presented both at the organizational level and at the level of individual patents. Organizational results show the distribution of CMI Hub-funded patents across critical materials technologies. They also examine the extent of the CMI Hub's influence on subsequent developments in critical materials and other technologies. Patent level results highlight individual CMI Hub-funded critical materials patents that have been particularly influential, as well as locating patents from other organizations that build extensively on CMI Hub-funded critical materials research.

2 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 in part upon tracing citation links between successive generations of patents. This tracing is designed to examine how CMI Hub-funded patents have influenced subsequent technological developments, both within and outside critical materials technology. The tracing 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 different patent systems, the analysis allows for a wide variety of possible linkages between CMI Hub-funded critical materials research and subsequent technological developments.

2.1 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 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.[1]

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. Patent citation analysis has also been used extensively to trace technological developments over time, again based on prior art references listed on patents, the idea being that the later patents build in some way on the earlier research.

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, Jan 2016.

2.2 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 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. Specifically, there are two types of links identified between CMI Hub-funded patents and subsequent generations of patents:

1. **Direct Links:** where a patent cites a CMI Hub-funded critical materials patent as prior art.
2. **Indirect Links:** where a patent cites an earlier patent, which in turn cites a CMI Hub-funded critical materials patent. The CMI patent is linked indirectly to the subsequent patent.

The idea behind adding the second generation of citations is that government funded entities, such as the CMI Hub, 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 commercial organization. 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

[1] Note that this analysis does not cover patents from other systems, notably patents from the Chinese, Japanese and Korean patent offices. This is because many patents from these systems do not 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.

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.

2.3 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.[2] In addition, in some systems—notably the United States—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, patent families are constructed for CMI Hub-funded critical materials patents, and also for all patents linked via citations to these CMI Hub-funded critical materials patents.

To construct these patent families, priority documents of the U.S., EPO, and WIPO patents are matched in order to group them into the appropriate families. It should be noted that the priority document need not necessarily be a U.S., EPO, or WIPO application. For example, a Japanese patent application may result in U.S., EPO, and WIPO patents, which are grouped in the same patent family because they share the same Japanese priority document.

2.4 Metrics Used in the Analysis

Table 1 contains a list of the metrics used in the analysis. These metrics are divided into four main groups—trends, assignees, technology distributions, and citation tracing metrics. Findings for each of these four groups of metrics can be found in the Results section of the report.

[2] It also means that patents from a given country’s system are not synonymous with inventions made in that country. Indeed, approximately half of all U.S. patent applications are from overseas inventors.

Table 1. List of Metrics Used in the Analysis

Metric
Trends
• Number of CMI Hub-funded critical materials patent families by year of priority application
• Number of CMI Hub-funded granted U.S. critical materials patents by issue year
• Overall number of critical materials patent families by priority year
• Percentage of critical materials patents families funded by the CMI Hub by priority year
Assignee Metrics
• Number of critical materials patent families for leading patenting organizations
• Assignees with largest number of critical materials patent families funded by the CMI Hub
Technology Metrics
• Patent classification distribution for CMI Hub-funded critical materials patent families (versus leading critical materials companies, all critical materials patents)
Citation Tracing Metrics
• Number of patent families linked via citations to CMI Hub-funded critical materials patents by patent classification
• Organizations with largest number of critical materials patent families linked via citations to CMI Hub-funded critical materials patent families
• Organizations with largest overall number of patent families linked via citations to CMI Hub-funded critical materials patent families
• CMI Hub-funded critical materials patent families linked via citations to largest number of subsequent critical materials/non-critical materials patent families
• Patent families linked via citations to most CMI Hub-funded critical materials patents

3 Methodology

The previous section of the report outlines the objective of the analysis—that is, to evaluate various characteristics of CMI Hub-funded critical materials patents, and to assess the influence of these patents on subsequent developments both within and outside critical materials technology. This section of the report describes the methodology used to implement the analysis.

3.1 Identifying CMI Hub-Funded Critical Materials Patents

The first step in this analysis involves defining the portfolio of CMI Hub-funded critical materials patents. As an initial dataset, the CMI Hub technology managers supplied a list of patents confirmed as funded by the CMI Hub. The next step then involved determining whether there are any additional patents funded by the CMI Hub that are not in this list.

To this end, the CMI Hub provided a list of the organizations with which it has partnered, and the names of scientists it has funded. The CMI Hub also supplied a list of the critical materials that have been the subject of research it has funded. Based on this list of materials, 1790 Analytics designed a custom patent filter and applied it to a database containing all DOE patents. This database was constructed by 1790 Analytics for previous DOE projects and was updated for the purposes of the current project. It contains more than 36,000 DOE-funded U.S. patents issued between January 1976 and June 2023 (the end point of the primary data collection for this analysis). Appendix A contains an overview of the processes involved in collating this all-DOE patent database.

Details of the patent filter used to identify critical materials patents within the DOE patent database are shown in Table 2.[3] This filter consists of combinations of Cooperative Patent Classifications and keywords. It is designed in such a way that patents referring to specific rare-earth materials are included without further restriction (Filter A). Meanwhile, patents referring to more widely-used materials (such as lithium or nickel) have to also include a patent classification related to materials production, refining or recycling. This classification restriction is added to prevent the inclusion of many less-relevant patents (e.g., all patents referring to lithium-ion or nickel metal hydride batteries). The form of the overall filter is (Filter A OR Filter B), so patents that qualify under either of the filters in Table 2 are selected.

The DOE-funded U.S. patents selected by the filter were manually cross-checked against the lists of CMI Hub partner organizations and funded researchers, resulting in a list of potential additional CMI Hub-funded patents. This list was supplied to the CMI Hub, along with a confidence level for each patent in the list, in terms of its likelihood of being funded by the hub (based on how many elements out of inventor, organization, and technology were present). The CMI Hub reviewed the list and returned it with a positive or negative flag in terms of whether each patent is funded by the CMI Hub.

Patents with a positive response for CMI Hub funding were added to the initial patent list supplied by the hub, resulting in an initial list of CMI Hub-funded U.S. patents. An additional search was then carried out 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. An extra search then covered U.S. patents that are continuations, continuations in part, or divisional applications of each of the patents in the CMI Hub-funded set. The result of this process is a final list of CMI Hub-funded patents (see Appendix B for details). This list contains 42 U.S. patents and 15 WIPO patents. (To date, there are no CMI Hub-funded EPO patents.) These 57 patents are grouped into 34 CMI Hub-funded patent families.

[3] The definition of “critical materials” used in this report is based on the list of materials that have been the subject of funding from the CMI Hub. This definition is not to be confused with other definitions of critical materials, for example that published by DOE, which includes a much longer list of materials: Office of Energy Efficiency and Renewable Energy. “U.S. Department of Energy Releases 2023 Critical Materials Assessment to Evaluate Supply Chain Security for Clean Energy Technologies.” U.S. Department of Energy. Posted July 31, 2023. https://www.energy.gov/eere/articles/us-department-energy-releases-2023-critical-materials-assessment-evaluate-supply.

Table 2. Filter Used To Identify DOE-Funded Critical Materials Patents

Filter A	
Title/Abstract	
Cerium	Praseodymium
Dysprosium	Terbium
Europium	Yttrium
Lanthanum	Rare earth elements
Neodymium	
Filter B	
Cooperative Patent Classification	
B22—Casting; Powder metallurgy	
C22B—Production and refining of metals	
C22C—Alloys	
C25C—Recovery and refining of metals	
H01F—Magnets	
Y02P 10/20—Recycling of metals	
AND	
Title/Abstract	
Lithium	Gallium
Cobalt	Germanium
Manganese	Indium
Nickel	Tellurium
Graphite	

3.2 Defining the Universe of Critical Materials Patents

Various elements of the analysis presented in this report examine the influence of CMI Hub-funded research on developments both within and beyond critical materials. It is therefore necessary to define the universe of critical materials patents. This was achieved by applying the filter in Table 2 to all EPO, U.S., and WIPO patents, not just those funded by DOE. Based on this filter, there are 8,022 critical materials patent families with priority dates between 2012 (the priority year of the first CMI Hub-funded patent family) and June 2023 (the end point for this analysis). These 8,022 patent families contain 3,727 EPO patents, 3,511 U.S. patents, and 6,385 WIPO patents.

There are also elements of the analysis that compare the CMI Hub against the leading organizations in critical materials technology. The 20 organizations with the largest number of patent families in the critical materials universe defined above are shown in Table 3.[4] The number of patent families listed in this table includes all variant names under which these companies have patents, taking into account all subsidiaries and acquisitions.

Table 3. Top 10 Patenting Critical Materials Companies

Company	Number of Critical Materials Patent Families
POSCO	193
Sumitomo Metal Mining	183
General Electric	96
Sumitomo Electric	96
Toyota	88
Siemens	82
Panasonic	79
Raytheon	73
Umicore	68
BASF	65

3.3 Constructing Citation Links

The processes described in this section resulted in three distinct patent sets—CMI Hub-funded critical materials patent families; critical materials patent families assigned to the leading organizations; and the universe of all critical materials patent families. The characteristics of these patent sets, along with the citation linkages among them, form the basis for the results described in the next section of this report. The citation analysis includes prior art listed on U.S., EPO, and WIPO patents, and required extensive data cleaning to account for differences in referencing formats across these systems.

4 Results

This section of the report outlines the results of an evaluation of the portfolio of CMI Hub-funded critical materials patents. The results are divided into two main sections. The first section examines trends in critical materials patenting over time and assesses the distribution of CMI Hub-funded patents across critical materials technologies. The second section reports the results of a citation analysis tracing forwards in time from CMI Hub-funded critical materials patents. The purpose of this citation analysis is to assess the influence of CMI Hub-funded research upon subsequent developments within and beyond

[4] All 10 of these organizations are companies. For clarity, they are referred to in the results section of the report as the leading critical materials 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 more complete description would be the leading patenting critical materials companies, but this is a cumbersome description to use throughout the results section of the report.

critical materials. The primary period of analysis in this report is from 2012 (the priority year of the earliest CMI Hub-funded patent family) to June 2023.

4.1 Overall Trends in Critical Materials Patenting

4.1.1 Trends in Critical Materials Patenting Over Time

Figure 1 shows the number of CMI Hub-funded critical materials patent families by priority year—i.e., the year of the first application in each patent family. This figure reveals that the earliest CMI Hub-funded patent family has a priority date in 2012, which is prior to the establishment of the CMI Hub in 2013. Further research revealed that this priority date is based on a provisional patent application, with the full patent application being filed in 2013.

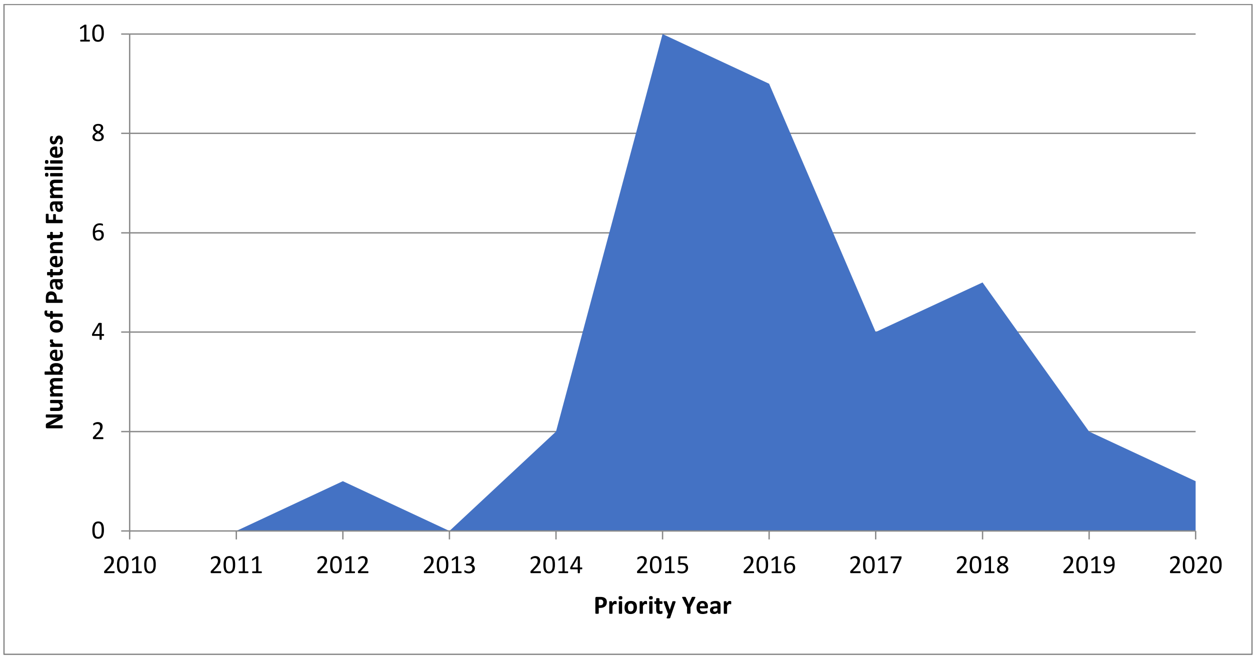

Figure 1. Number of CMI Hub-funded critical materials patent families by priority year

To date, the peak in the number of CMI Hub-funded patent families came in 2015, when 10 families were filed. The number of CMI Hub-funded families remained high at nine in 2016, before starting to decline from 2017 onwards. It should be noted that more recent years may be affected by time lags associated with the patenting process. In most systems, patent applications are published 18 months after they are filed and remain confidential until that point. This explains the lack of patent families beyond 2020 in Figure 1. Overall, there are 34 CMI Hub-funded patent families to date, with priority years between 2012 and 2020. These patent families are listed in Table 4 (with the representative patent being the first granted U.S. patent in each family).

Table 4. List of CMI Hub-funded Critical Materials Patent Families

Family ID	Priority Year	Representative Patent	Issue Year	Assignee	Title
49234132	2012	US9691545	2017	Lawrence Livermore National Security	Developing bulk exchange spring magnets
55438155	2014	US9337010	2016	Lawrence Livermore National Security; General Electric	Fluorescent lighting with aluminum nitride phosphors
55163482	2014	US9725788	2017	Iowa State University	Recovering heavy rare earth metals from magnet scrap
58187932	2015	US9777346	2017	Battelle Energy Alliance	Methods for recovering metals from electronic waste, and related systems
57324542	2015	US9938628	2018	General Electric	Composite nanoparticles containing rare earth metal and methods of preparation thereof
57776349	2015	US10323299	2019	Iowa State University	Recovering rare earth metals from magnet scrap
57836600	2015	US10029920	2018	Iowa State University	Separation of terbium(iii, iv) oxide
66826134	2015	US10323300	2019	U.S. Department of Energy	Process for recycling rare earth magnets
57397123	2015	US9968887	2018	UT-Battelle	Membrane assisted solvent extraction for rare earth element recovery
58662639	2015	US10643776	2020	UT-Battelle	System and method for the recycling of rare earth magnets
60088542	2015	US10689727	2020	UT-Battelle	Methods for liquid extraction of rare earth metals using ionic liquids
57686119	2015	US9963770	2018	UT-Battelle; Eck Industries; Lawrence Livermore National Laboratory; Iowa State University	Castable high-temperature remodified Al alloys
57015686	2015	US10407535	2019	UT-Battelle; Washington State University	3D printable liquid crystalline elastomers with tunable shape memory behavior and bio-derived renditions
62020297	2016	US10533239	2020	Battelle Energy Alliance; University of Idaho	Methods of recovering rare earth elements from a material
61016898	2016	US11090579	2021	Iowa State University	Separating rare earth metal oxalates
61561491	2016	US10648063	2020	Iowa State University	Dissolution and separation of rare earth metals

59360783	2016	US10586640	2020	Iowa State University; Lawrence Livermore National Laboratory; UT-Battelle	Neodymium-iron-boron magnet with selective surface modification, and method of producing same
60039980	2016	US10266915	2019	UT-Battelle; Alger Alternative Energy	Composition for recovery of lithium from brines, and process of using said composition
60659315	2016	US11535912	2022	UT-Battelle; Eck Industries	Structural direct-write additive manufacturing of molten metals
61242168	2016	US10782193	2020	UT-Battelle; Iowa State University	High command fidelity electromagnetically driven calorimeter
59485427	2016	US10584403	2020	UT-Battelle; University of Tennessee; Iowa State University; Eck Industries	Surface-hardened aluminum-rare earth alloys and methods of making the same
59362642	2016	US10253261	2019	UT-Battelle; Washington State University	Stimuli-responsive liquid crystalline networks
66815651	2017	US11149356	2021	Battelle Energy Alliance	Methods of forming metals using ionic liquids
62782292	2017	US10196708	2019	Lawrence Livermore National Security; Battelle Energy Alliance	Engineered microbes for rare earth element adsorption
66813810	2017	US11649537	2023	Iowa State University	Permanent magnet alloys for gap magnets
63166817	2017	US11590717	2023	UT-Battelle; Iowa State University	Extrudable magnetic ink and novel 3d printing method to fabricate bonded magnets of complex shape
67299818	2018	US10954585	2021	Battelle Energy Alliance	Methods of recovering rare earth elements
68464992	2018	US11040296	2021	UT-Battelle	Lipophilic diglycolamide compounds for extraction of rare earth metals from aqueous solutions
69523806	2018	US11293078	2022	UT-Battelle	Separation of rare earth elements using supported membrane solvent extraction
71071838	2018	US11611266	2023	UT-Battelle	Automated recovery of rare earth permanent magnets from electric machines
67843213	2018	US11253820	2022	UT-Battelle; All American Lithium	Lithium extraction composite for recovery of lithium from brines, and process of using said composition
74680784	2019	US11565318	2023	UT-Battelle; University of Tennessee; Eck Industries	Reactive matrix infiltration of powder preforms

71266791	2019	US11365463	2022	UT-Battelle; University of Tennessee; Eck Industries; Iowa State University; Colorado School of Mines; Lawrence Livermore National Security	Production of castable light rare earth rich light metal compositions from direct reduction processes
76761017	2020	US11608546	2023	UT-Battelle; Eck Industries; Iowa State University; Lawrence Livermore National Security; University of Tennessee	Aluminum-cerium-manganese alloy embodiments for metal additive manufacturing

Figure 2 shows the number of CMI Hub-funded granted U.S. patents by issue year (i.e., the year in which they were granted). The first CMI Hub-funded U.S. was granted in 2016, and thereafter, the number of patents by year increased steadily, peaking at nine granted in 2020. After that, the number of CMI Hub-funded U.S. patents declined slightly to six in 2021 and seven in 2022. Figure 2 shows five CMI Hub-funded U.S. patents in 2023, but it should be noted that this is only for the first 6 months of the year. It may be that the final number of CMI Hub-funded U.S. patents shows an increase in 2023 once the year is complete.

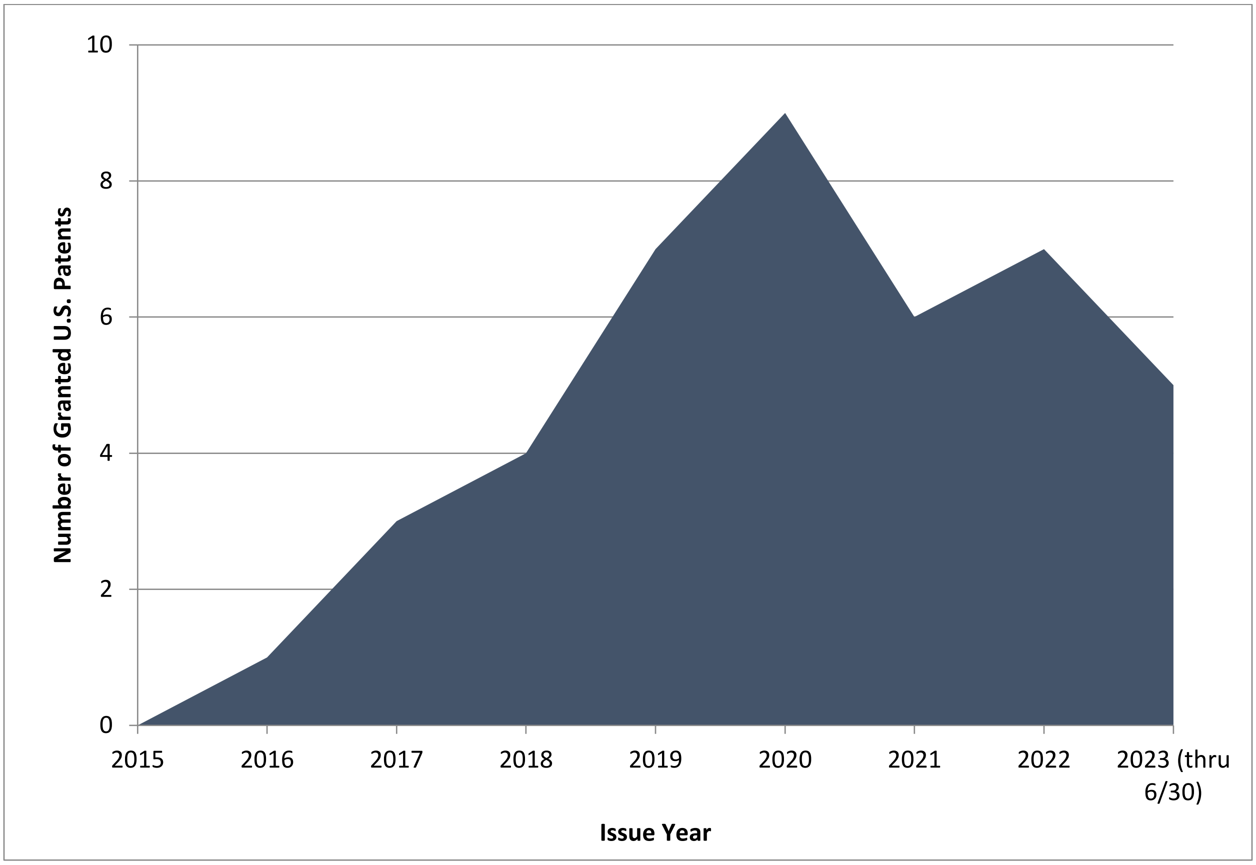

Figure 2. Number of CMI Hub-funded critical materials U.S. patents by issue year

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 2015 and 2016 (Figure 1) resulting in granted U.S. patents in 2019 and 2020 (Figure 2). These time lags can also be seen in Figure 3, which shows CMI Hub-funded patent family priority years alongside issue years for CMI Hub-funded granted U.S. patents. Although the number of documents involved is relatively small, it is possible to see how a spike in patent families filed in 2015–2016 led to a peak in U.S. patents in 2019–2020.

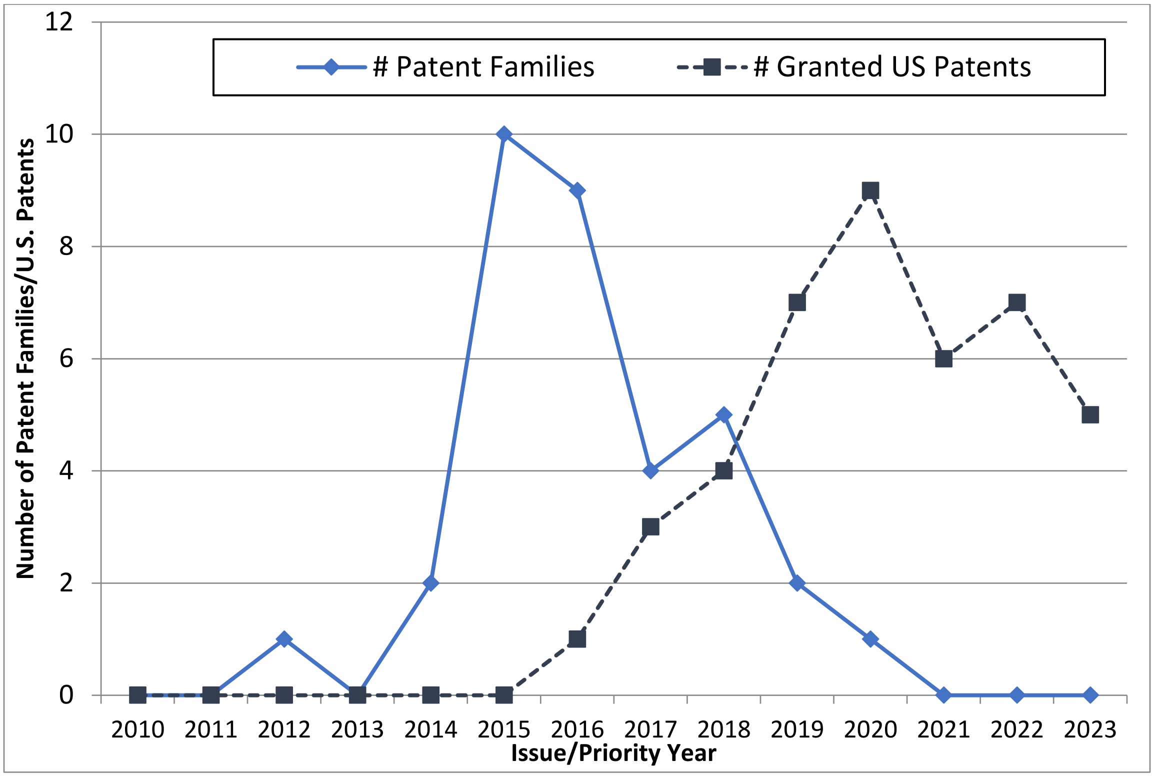

Figure 3. Number of CMI Hub-funded critical materials patent families (by priority year, shown as the solid line) and granted U.S. patents (by issue year, shown as the dashed line)

Figures 1–3 focus on CMI Hub-funded critical materials patent families. Figure 4 broadens the scope and shows the overall number of critical materials patent families by priority year (based on PTO, EPO, and WIPO filings). This chart covers the period back to 2000, in order to provide insights into the overall trends in critical materials patenting both before and after the CMI Hub was established in 2013. Figure 4 reveals that there has been a steady growth in critical materials patenting since 2000. In that year, 570 critical materials were filed, a number that increased to 775 by 2013 when the CMI Hub was founded. Since that time, the number of critical materials patent families has continued to increase, peaking at 847 in 2016, and remaining at around the same level after that time, with 825 families in 2021, the most recent year shown in Figure 4.

Figure 5 shows the percentage of critical materials patent families by priority year that were funded by the CMI Hub. This figure reveals that CMI Hub-funded patent families represented 1.4% of all critical materials patent families in 2015 and 1.1% in 2016. Since then, the percentage of critical materials patent families funded by the CMI Hub has fallen below 1% in each year. Overall, 0.4% of critical materials patent families filed from 2012 onwards were funded by the CMI Hub.

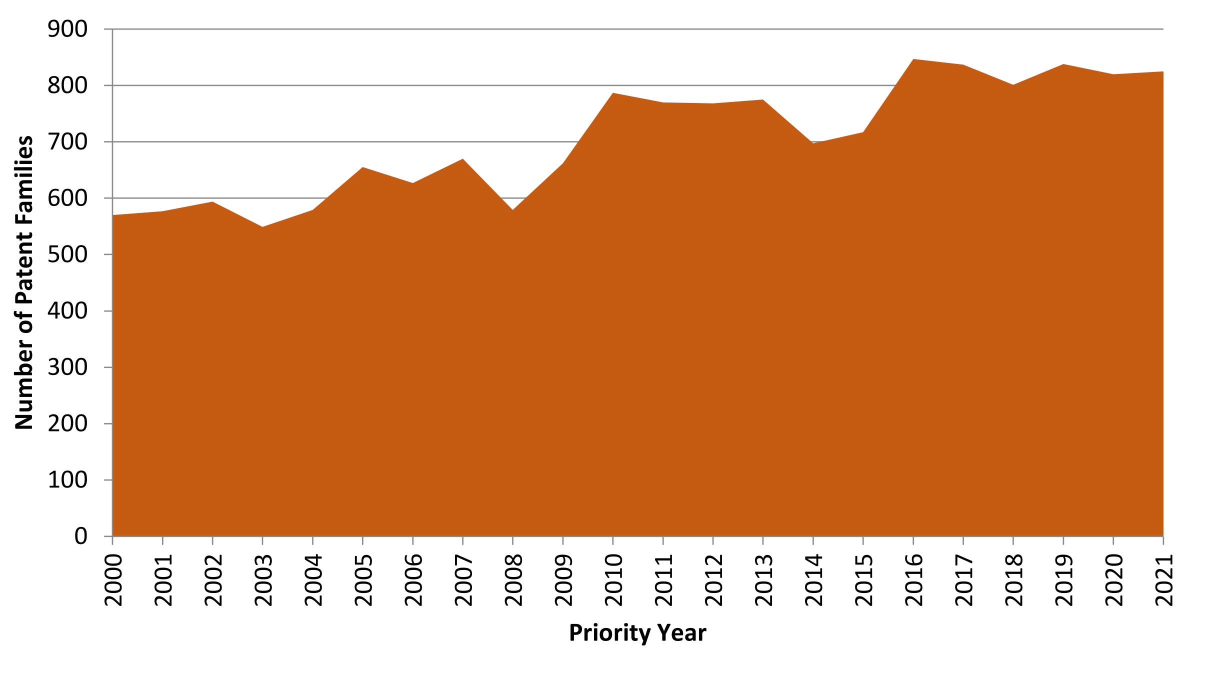

Figure 4. Total number of critical materials patent families by priority year (2000–2021)

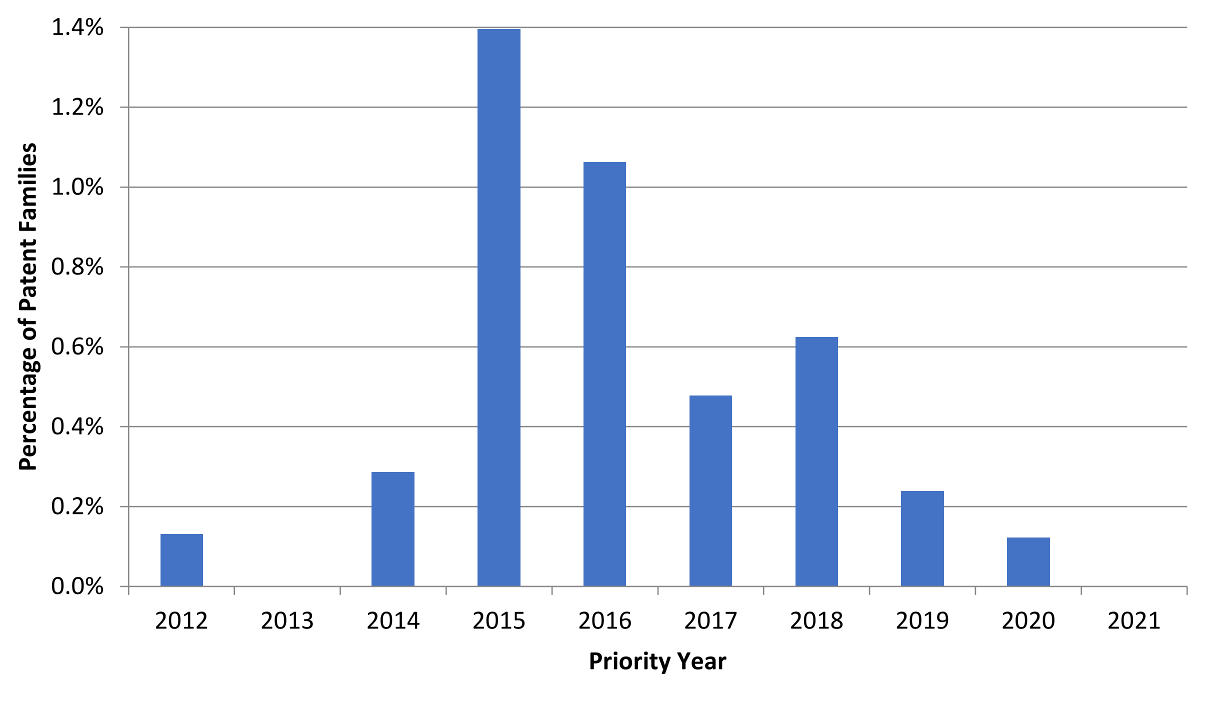

Figure 5. Percentage of critical materials patent families funded by the CMI Hub by priority year

4.1.2 Leading Critical Materials Assignees

The ten leading patenting companies in critical materials (based on patent families with priority dates from 2012 onwards) are listed above in Table 3. Figure 6 shows the same information in graphical form, while also including CMI Hub-funded patent families. This figure is headed by POSCO with 193 critical materials patent families, followed by Sumitomo Metal Mining with 183 families. There is then a gap to General Electric and Sumitomo Electric, each with 96 critical materials patent families, followed by Toyota (88 families), Siemens (82 families) and Panasonic (79 families). The CMI Hub is listed at the bottom of Figure 6 with 34 patent families, a portfolio that is smaller than the leading companies but is in a similar scale to most of the other portfolios—other than POSCO and Sumitomo Metal Mining.

It is interesting to note the geographical distribution of the leading critical materials companies. Out of these ten companies, five are based in Asia, three in North America and two in Europe. This reflects the international nature of critical materials research. It also reinforces the earlier note that focusing on USPTO, EPO and WIPO filings does not lead to the exclusion of companies based in Asia.

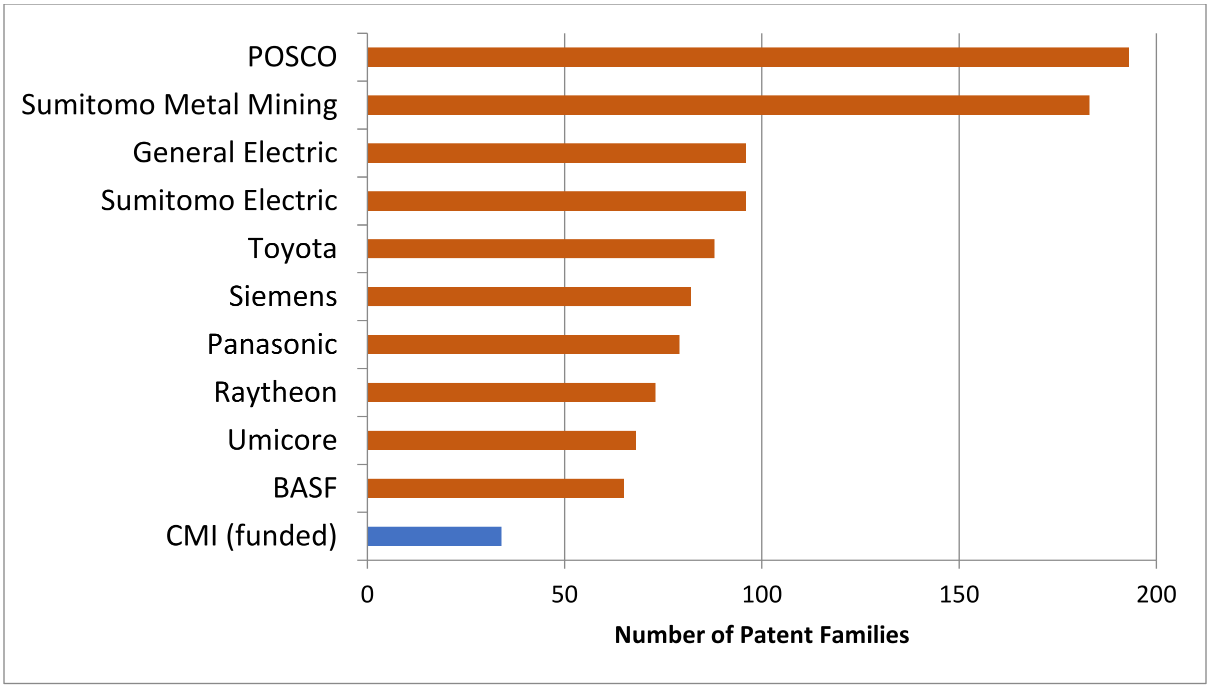

Figure 6. Top 10 critical materials companies (based on number of patent families since 2012)

4.1.3 Assignees of CMI Hub-Funded Critical Materials Patents

The CMI Hub-funded critical materials patent portfolio is constructed somewhat differently from the portfolios of the top ten companies listed in Figure 6. Specifically, the CMI Hub's 34 patent families are funded by CMI, but they are not necessarily assigned to DOE itself. For example, the CMI Hub has funded research projects at companies and DOE national labs. In such cases, the assignees of any resulting patents may be the respective companies or DOE lab managers.

Figure 7 shows the leading assignees on CMI Hub-funded patent families. This figure is headed by UT-Battelle, with 19 CMI Hub-funded patent families resulting from its management of Oak Ridge National

Laboratory. It is followed in Figure 7 by two other DOE lab managers—Iowa State University (Ames National Laboratory) with 13 CMI Hub-funded patent families, and Lawrence Livermore National Security (Lawrence Livermore National Laboratory) with seven families. There are three companies listed in Figure 7—Eck Industries with six CMI Hub-funded patent families, and General Electric and TerraLithium each with two patent families (with the latter patent families originally assigned to All American Lithium and Alger Alternative Energy).

It should be noted that a number of CMI Hub-funded patent families are co-assigned to multiple organizations. For example, there are patent families that are co-assigned to all four of the organizations at the head of Figure 7. These families are whole counted for each organization. Hence, the overall count in Figure 7 is higher than the total of 34 CMI Hub-funded patent families.

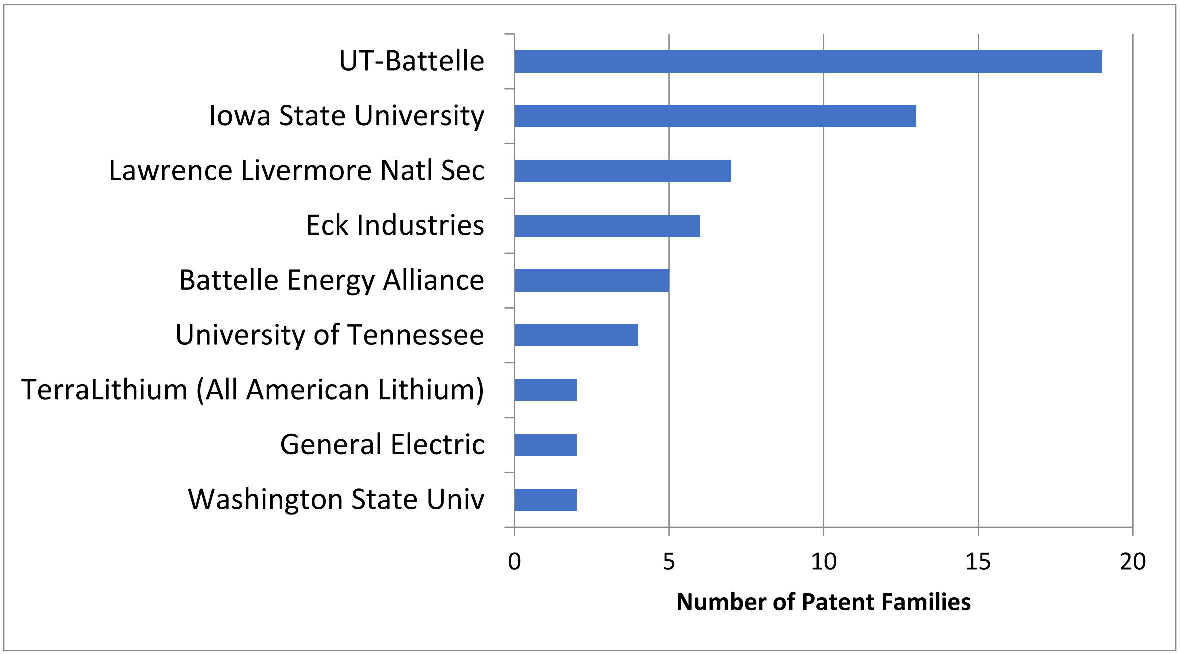

Figure 7. Assignees with the most CMI Hub-funded critical materials patent families

4.1.4 Distribution of Critical Materials Patents across Patent Classifications

This section of the report examines the technological focus of CMI Hub-funded critical materials patents, versus the focus of patents assigned to leading critical materials companies, plus critical materials patents in general. The analysis is based on the distribution of each of these three groups of patents across Cooperative Patent Classifications (CPCs).[5]

Figure 8 contains the seven CPCs that are most common among all critical materials patent families. Specifically, this figure shows the percentage of all critical materials patent families that are in each of these CPCs. It also shows the percentage of CMI Hub-funded patent families, plus the percentage of families assigned to the 10 leading companies, in each of these CPCs. Hence, the purpose of this chart is

[5] CPCs are part of 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.

to show the main research areas within critical materials as a whole, and how these areas are represented in the portfolios of CMI Hub-funded patents and critical materials patents assigned to the leading companies.

The results in Figure 8 reveal an interesting pattern. Four out of the seven CPCs in this figure are related to ferrous alloys. For example, 16% of all critical materials patents are classified as CPC C22C 38/02. This classification covers ferrous alloys containing silicon. Figure 8 also contains CPCs related to ferrous alloys incorporating manganese, aluminum, and indium/magnesium. The patent families assigned to the leading companies have a notable presence in each of these CPCs. In contrast, the portfolio of CMI Hub-funded patents has little presence in the CPCs related to ferrous alloys, with only a single patent family describing ferrous alloys containing aluminum. Among the CPCs in Figure 8, the CMI Hub patent portfolio is much more focused in a single area, namely metals recycling (CPC Y02P 10/20), with 47% of CMI Hub-funded patent families being classified as such.

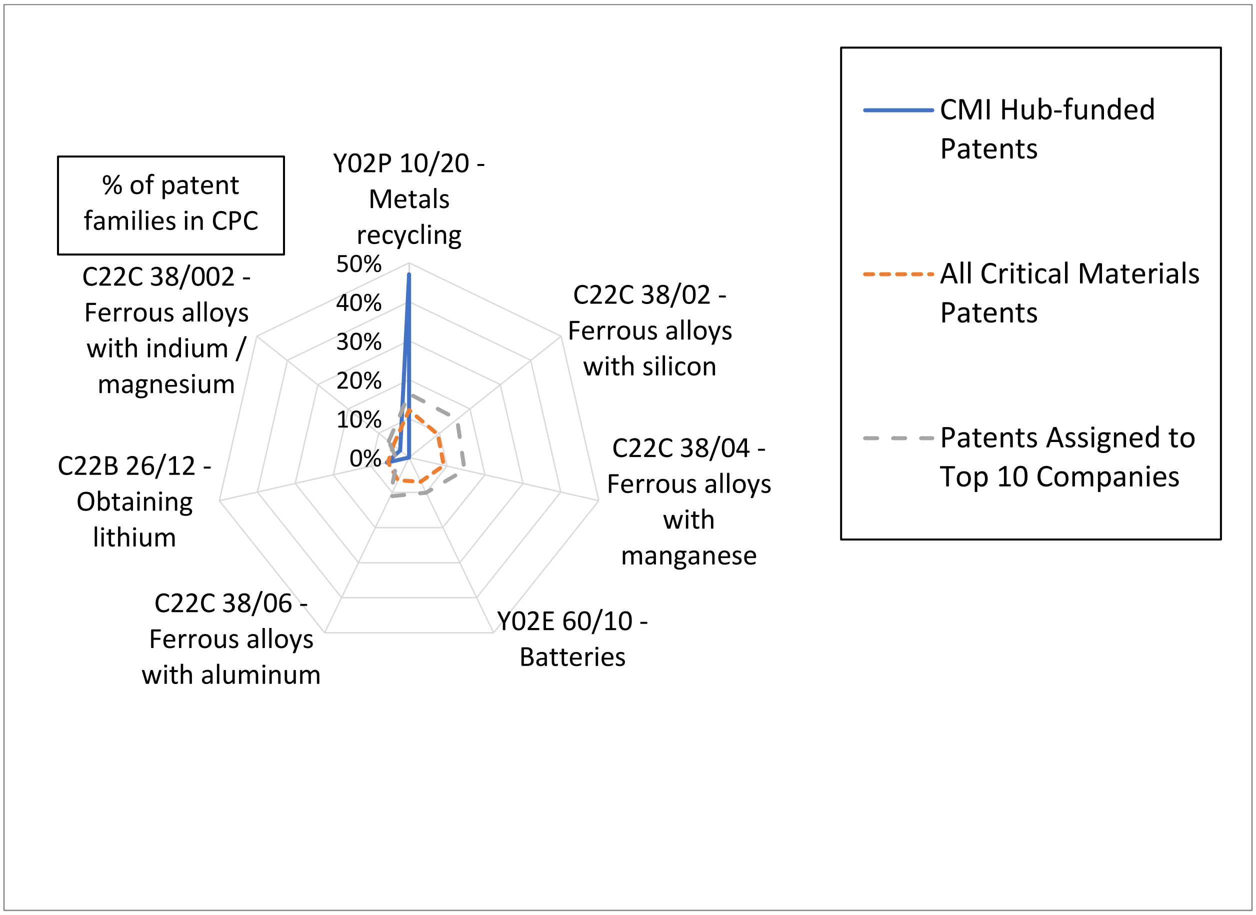

Figure 8. The percentage of critical materials patent families across CPCs for CMI Hub-funded patents, all critical materials patents, and patents assigned to the 10 companies

Figure 9 compares the CPC distribution of CMI Hub-funded critical materials patent families across two time periods—families filed through 2015, and those filed from 2016 onwards (these dates are selected to divide the patents into two groups of approximately equal size). This figure reveals a slight shift in the

CPC distribution across these two time periods. In the earlier time period, there was no dominant CPC, with similar numbers of patent families across all CPCs in the figure. More recently, there is a much greater focus in two areas—metals recycling (CPC Y02P 10/20) and obtaining rare earth materials (CPC C22C 21/00). Two-thirds of all CMI Hub-funded patent families filed after 2015 are classified as the former CPC and 52% classified as the latter CPC. There are also notable percentages of recent CMI Hub-funded patents directed to aluminum alloys and additive manufacturing. This suggests that these four areas have become a major focus of CMI Hub-funded research in recent years, perhaps to a greater extent than for the leading companies (based on the results in Figure 8). CMI Hub funding may thus be helping to fill a research gap not addressed extensively by the leading companies.

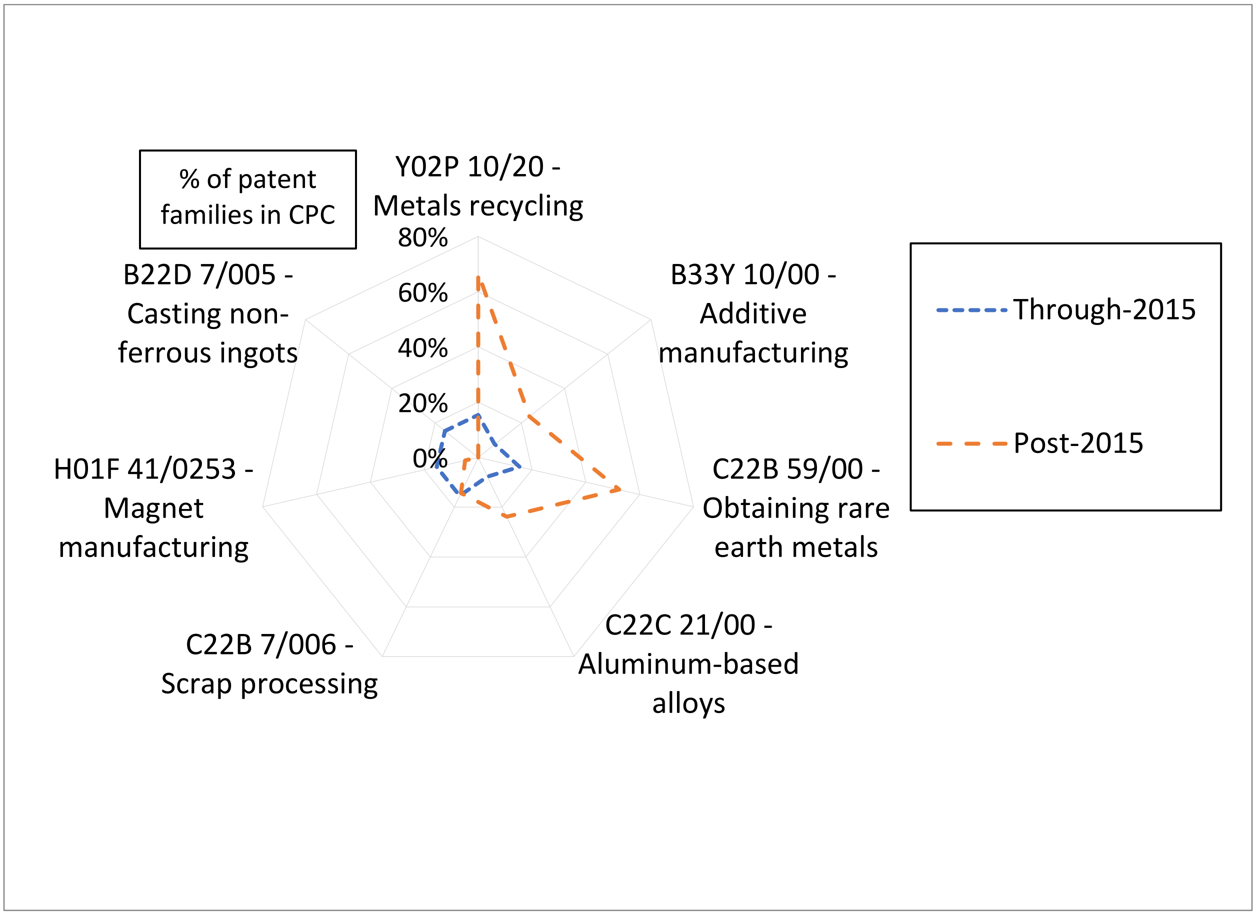

Figure 9. Percentage of CMI Hub-funded critical materials patent families in the most common CPCs across two time periods (through-2015 and post-2015)

4.2 Tracing the Influence of CMI Hub-Funded Critical Materials Patents

This section of the report outlines the results of an analysis tracing the influence of CMI Hub-funded research on subsequent developments both within and beyond critical materials technologies. The tracing starts with the set of CMI Hub-funded critical materials patent families. It then traces forwards through two generations of citations to these CMI Hub-funded patent families. These include citations listed on U.S., EPO, and WIPO patents. The results of this tracing are presented at three levels—technologies, organizations, and individual patents.

When assessing the results of the tracing analysis, it should be kept in mind that many of the CMI Hub-funded patent families are relatively recent. As such, they have not had much time to become linked via citations to subsequent generations of technology, especially given the time lags associated with the patenting process. That said, the tracing analysis does reveal numerous examples where CMI Hub-funded research has influenced downstream innovations. In total, there are 68 patent families linked via citations to earlier CMI Hub-funded patents (plus eleven cases where CMI Hub-funded families are linked via citations to earlier CMI Hub-funded patents).

4.2.1 Technology Level Results

Figure 10 lists the CPCs with the largest number of patent families linked via citations to earlier CMI Hub-funded critical materials patents.[6] These CPCs reflect the influence of CMI Hub-funded research across technologies. The CPCs are shown in two different colors—i.e. those related to critical materials technology (dark green) and those beyond critical materials (light green). The former represent the influence of CMI Hub-funded patents on critical materials technology itself, while the latter represent spillovers of the influence of CMI Hub-funded critical materials research into other technology areas.

Ten of the 14 CPCs in Figure 10 are related to critical materials. Among the most prominent of these CPCs are Y02P 10/20 (metals recycling), C22B 59/00 (obtaining rare earth metals), and C22B 26/12 (obtaining lithium). These technologies were highlighted earlier as being prominent among CMI Hub-funded patents themselves. As such, this finding reinforces the influence of the CMI Hub on innovations related to two of its focus areas—i.e., driving reuse and recycling as well as diversifying the supply of materials. There are also CPCs in Figure 10 related to aluminum-based alloys and powder metallurgy, reflecting CMI's influence in these technologies.

Beyond critical materials technology, there are four CPCs in Figure 10 that are not focused specifically on critical materials. These four CPCs are all related to additive manufacturing, three of them to additive manufacturing processes, materials, and products and the fourth to powder bed fusion, which is one of the most widely-used processes in additive manufacturing. The presence of these CPCs in Figure 10 thus suggests that the CMI Hub's critical materials research has had a notable spillover influence in additive manufacturing.

[6] Patents typically have numerous CPCs attached to them, reflecting different aspects of the invention they describe. In this analysis, all CPCs attached to the patents linked via citations to earlier CMI Hub-funded critical materials patent families are included. Also, the figure includes a small percentage of "self-citations"—i.e. cases where CMI Hub-funded patent families are linked via citations to earlier CMI Hub-funded families.

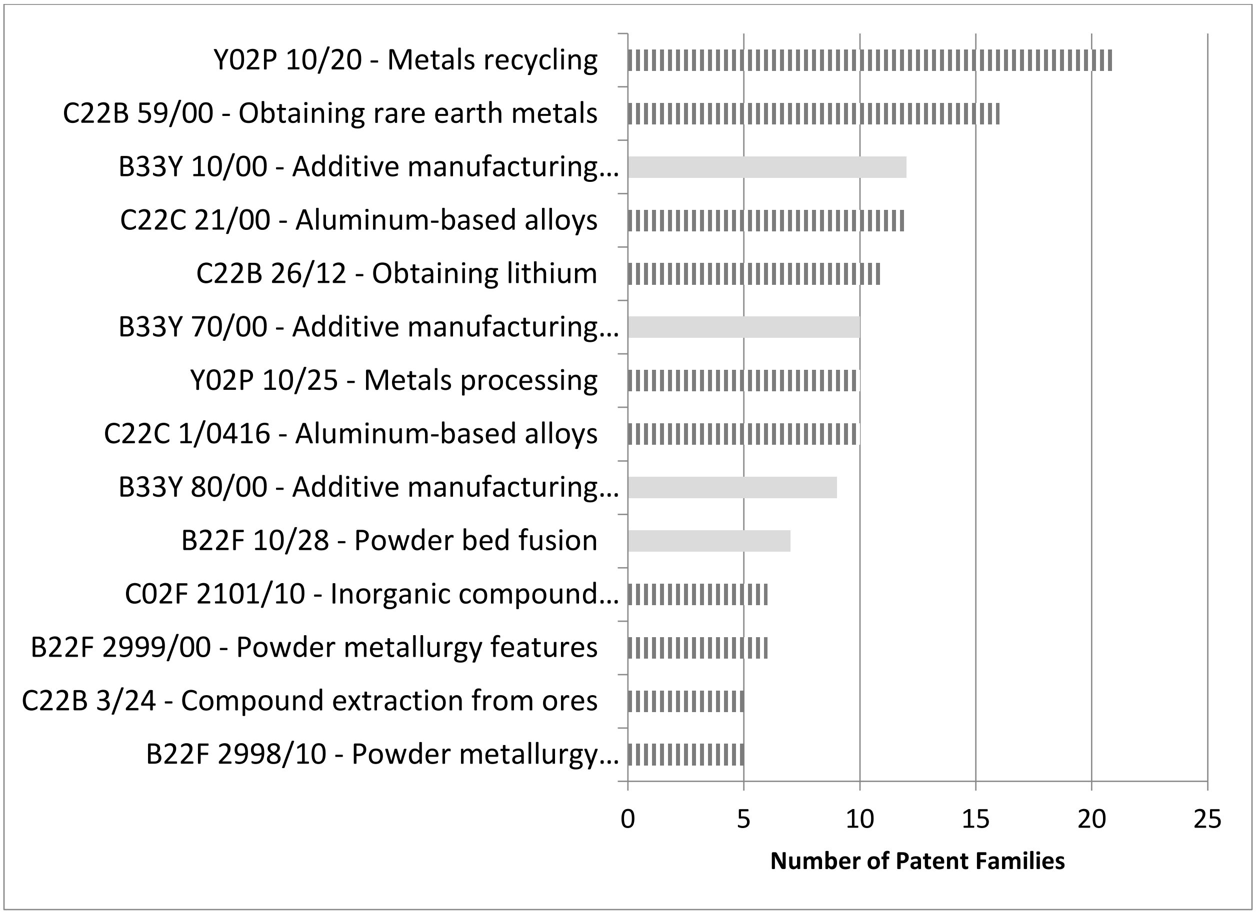

Figure 10. Number of patent families linked via citations to earlier CMI Hub-funded critical materials patents by CPC (dark gray lines=critical materials related; solid light gray=other)

4.2.2 Organizational Level Results

The organizations with critical materials patent families linked via citations to earlier CMI Hub-funded critical materials patents are shown in Figure 10 (details of the linked patent families from these organizations are provided in Appendix C). There are three companies at the head of this figure, each of which has two patent families linked to earlier CMI Hub-funded patents. The first of these companies is Arconic, which has two patent families outlining aluminum alloys containing iron and rare earth elements (see, for example, patent number WO2020081150). These patent families are linked via citations to earlier CMI Hub-funded patents assigned to UT-Battelle, outlining high-temperature aluminum alloys and additive manufacturing of molten metals. Hamilton Sundstrand (now part of Raytheon) also has two patent families in Figure 11. These patent families (see, for example, patent number US11,185,923) outline additive manufacturing of aluminum alloys and are linked to earlier CMI Hub-funded patents for aluminum alloys also assigned to UT-Battelle. The Arconic and Hamilton Sundstrand patent families are examples of CMI's influence upon developments in additive manufacturing, which was highlighted in Figure 10.

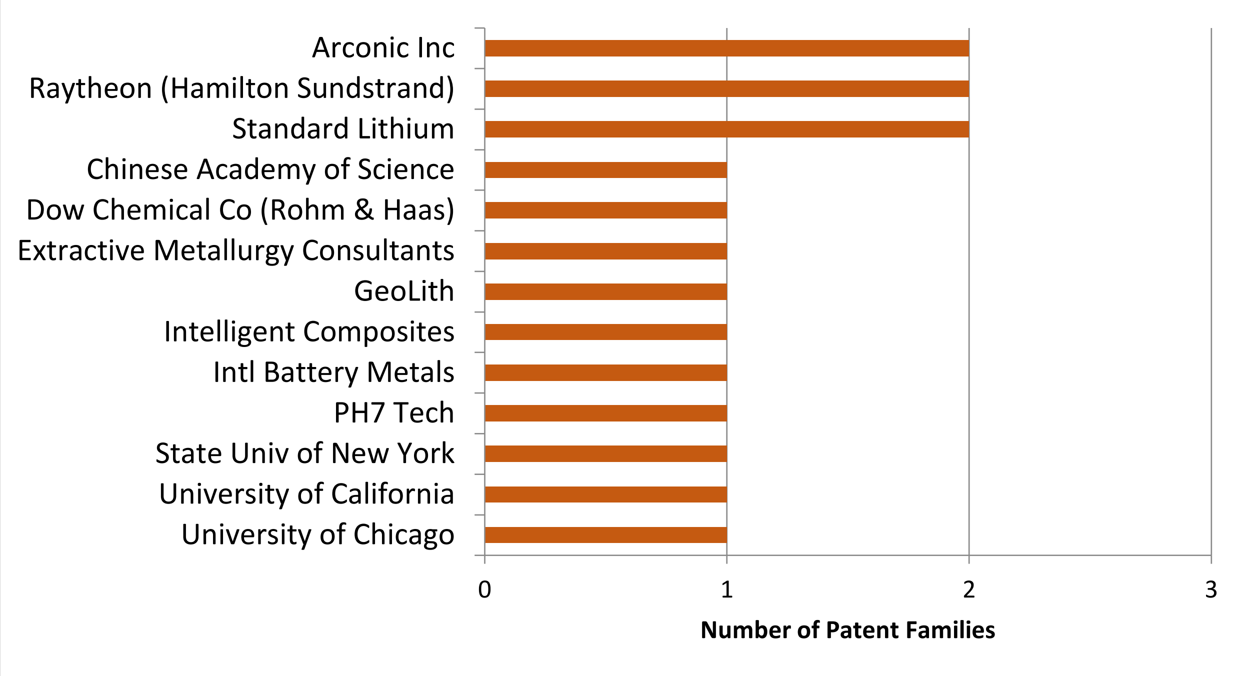

Figure 11. Organizations with critical materials patent families linked via citations to earlier CMI Hub-funded critical materials patents

Standard Lithium is the third company in Figure 11 with two patent families linked via citations to earlier CMI Hub-funded patents. These two patent families are both concerned with extracting lithium from brines (see, for example, patent number US11,518,686) and linked via citations to earlier CMI Hub-funded patents that also outline lithium extraction. The patent families assigned to GeoLith (e.g., patent number EP4232192), Extractive Metallurgy Consultants (e.g., patent number US11,732,326), and the University of Chicago (e.g., patent number WO2023027911) are also related to lithium extraction, reflecting the influence of CMI Hub-funded patents in this technology area. Other technologies covered by the patents in Figure 11 include extraction of rare earth materials from ores (Chinese Academy of Science; e.g., patent number WO2020211304), and recovery of precious metals using solvents (pH7 Technologies; patent number WO2023065044), reflecting additional areas of the CMI Hub's influence on developments in critical materials technology.

Figure 12 broadens the scope of the tracing analysis and shows the organizations with the largest overall number of patent families linked via citations to earlier CMI Hub-funded critical materials patent families (details of the linked patent families from these organizations are provided in Appendix D). Note that this figure includes all such patent families assigned to these organizations, not just their patent families describing critical materials technology. Cooper Companies is at the head of Figure 12, with four patent families linked via citations to earlier CMI Hub-funded critical materials patents. Cooper is a medical device company, and its patent families in Figure 12 (see, for example, patent number US10,859,868) are all concerned with liquid crystal contact lenses. They are linked via citations to an earlier CMI Hub-funded patent family (see e.g., patent number US10,407,535) describing three-dimensionally (3D) printed liquid crystal elastomer compositions. As such, this is an example of a spillover where CMI Hub-funded technology has influenced downstream innovation in a different field.

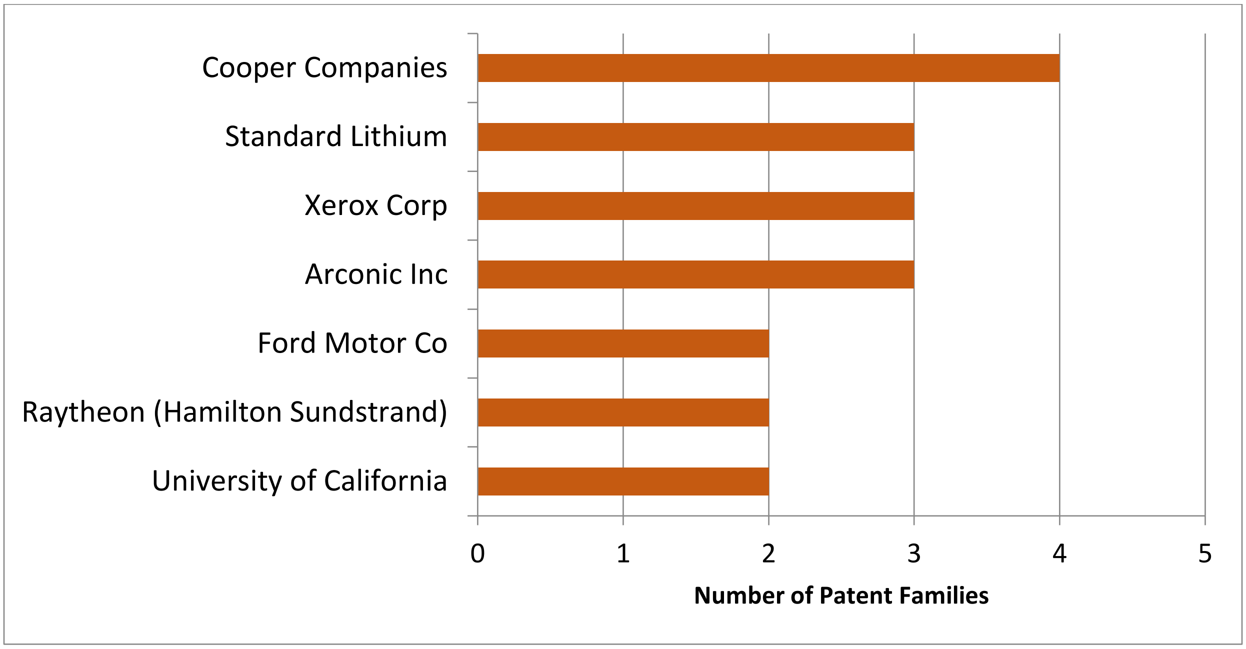

Figure 12. Organizations with the most overall patent families linked via citations to CMI Hub-funded critical materials patents

Other companies in Figure 12 (excluding Standard Lithium, Arconic, and Raytheon—which were all shown in Figure 11) include Xerox and Ford. Xerox has three patent families in Figure 12 related to printing systems (see, for example, patent number US11,498,354). These Xerox patent families are linked via citations to an earlier CMI Hub-funded calorimeter patent (patent number US10,782,193). Meanwhile, Ford has two patent families that are linked via citations to earlier CMI Hub-funded patents. These two Ford families (see, for example, patent number US11,208,154) outline vehicle body structure reinforcement using additive manufacturing. They are linked via citations to the CMI Hub-funded liquid crystal elastomer patent referred to above, which also describes additive manufacturing techniques. Again, these are examples of CMI Hub-funded patents helping to form part of the foundation for subsequent innovations in different industries.

4.2.3 Patent Level Results

This section of the report drills down to identify individual CMI Hub-funded critical materials patent families linked via citations to subsequent innovations. Looking in the opposite direction, this section also highlights patents that have extensive citation links to earlier CMI Hub-funded critical materials research.

Table 5 shows the CMI Hub-funded critical materials patents linked via citations to the largest number of subsequent patent families. These subsequent families are divided into two groups, based on whether they are within or beyond critical materials technology. This highlights which CMI Hub-funded patent families have been particularly influential within critical materials technology, and which have had a wider impact beyond critical materials.

The CMI patent family at the top of Table 5 (see patent number US10,407,535) is co-assigned to UT-Battelle and Washington State University. This is the patent family discussed earlier that outlines 3D-printed liquid crystal elastomers. It is linked to nine subsequent patent families, all of which are defined as being beyond critical materials technology. These linked patent families cover both additive manufacturing processes and specific applications for liquid crystal materials, notably in contact lenses. There is also a second CMI Hub-funded patent family near the head of Table 5 (see patent number US11,535,912) related to additive manufacturing. This patent family, which is co-assigned to UT-Battelle and Eck Industries, details additive manufacturing of materials with high melting points, such as molten metals. It is linked via citations to eight subsequent patent families, three of them from within critical materials (primarily concerned with aluminum alloys) and five of them from other technologies (notably additive manufacturing).

There are two other CMI Hub-funded patent families in Table 5 that are linked via citations to eight subsequent patent families each. In both cases, four of these subsequent patent families are from within critical materials technology, with the other four being from other technologies. The first of these CMI Hub-funded patent families (see patent number US9,963,770) describes cerium-modified aluminum alloys. It is linked via citations to subsequent families for improved aluminum alloys assigned to various organizations, including Arconic, Hamilton Sundstrand (Raytheon) and the University of Texas. The second CMI Hub-funded patent family (see patent number US10,266,915) outlines recovery of lithium from brines. It is linked via citations to subsequent patent families covering both lithium recovery (assigned to Standard Lithium and Summit Nanotech) and other technologies such as carbon capture (assigned to Heimdal) and removing impurities from cleaning fluids (assigned to Carefusion 2200 Inc.). It is also worth noting that Table 5 includes patents for other CMI Hub-funded technologies, including recycling patents assigned to Battelle Energy Alliance (see patent number US9,777,346) and UT-Battelle (see patent number US10,643,776).

Table 5 identifies CMI Hub-funded patent families linked particularly strongly to subsequent technological developments. Table 6 shows the opposite and identifies patent families linked via citations to the most CMI Hub-funded critical materials patent families. The patent family at the top of Table 6 (see patent number US11,408,056) describes aluminum alloys containing cerium and graphite. It is assigned to Intelligent Composites (whose CEO is also a vice president at Eck Industries, a CMI Hub partner organization). This patent family is linked via citations to three earlier CMI Hub-funded patent families for aluminum alloys, each of which is co-assigned to Eck Industries. It thus appears to be an example of CMI Hub-funded research being employed in a practical application, specifically the use of advanced aluminum alloys in vehicle components.

The second patent family in Table 6 (see patent number US11,260,475) is assigned to the University of Texas, and describes additive manufacturing of aluminum alloys. It is linked via citations to two earlier CMI Hub-funded patent families for aluminum alloys. Meanwhile, the other two patent families in Table 5 are both assigned to Hamilton Sundstrand (now part of Raytheon). These patent families (see, for example, patent number US11,192,188) also describe additive manufacturing of aluminum alloys, and are linked to the same two CMI Hub-funded aluminum alloy patent families. As such, the patent families in Table 6 are all examples of subsequent technologies building upon a series of CMI Hub-funded aluminum alloy patents.

Table 5. CMI Hub-Funded Critical Materials Patent Families Linked via Citations to Most Subsequent Critical Materials/Other Patent Families

Family Number	Priority Year	Representative U.S. Patent Number	Number of Linked Families	Number of Linked Critical Materials Families	Assignee	Title
57015686	2015	10407535	9	0	UT-Battelle; Washington State Univ	3D printable liquid crystalline elastomers with tunable shape memory behavior and bio-derived renditions
57686119	2015	9963770	8	4	UT-Battelle; Eck Industries; Livermore Natl Security LLC; Iowa State Univ	Castable high-temperature Ce-modified Al alloys
60039980	2016	10266915	8	4	UT-Battelle; Alger Alternative Energy	Composition for recovery of lithium from brines, and process of using said composition
60659315	2016	11535912	8	3	UT-Battelle; Eck Industries	Structural direct-write additive manufacturing of molten metals
59485427	2016	10584403	6	3	UT-Battelle; Univ Tennessee; Iowa State Univ; Eck Industries	Surface-hardened aluminum-rare earth alloys and methods of making the same
57397123	2015	9968887	5	1	UT-Battelle	Membrane assisted solvent extraction for rare earth element recovery
58187932	2015	9777346	5	2	Battelle Energy Alliance	Methods for recovering metals from electronic waste, and related systems
58662639	2015	10643776	5	1	UT-Battelle	System and method for the recycling of rare earth magnets

Table 6. Patent Families Linked via Citations to Most Earlier CMI Hub-funded Critical Materials Patent Families

Family Number	Priority Year	Representative U.S. Patent Number	Number of Linked Families	Assignee	Title
65229684	2017	11408056	3	Intelligent Composites Inc	Aluminum based alloy containing cerium and graphite
65231466	2017	11260475	2	University of Texas	Method and system for powder bed fusion additive manufacturing of crack-free aluminum alloys
62235821	2017	11192188	2	Raytheon Co. (Hamilton Sundstrand)	Method of manufacturing aluminum alloy articles
62217802	2017	11185923	2	Raytheon Co. (Hamilton Sundstrand)	Method of manufacturing aluminum alloy articles

5 Conclusions

This report describes the results of an analysis of CMI Hub-funded critical materials research. The purpose of the report is to assess various characteristics of patents awarded for CMI Hub-funded innovations in critical materials technology and determine the extent to which CMI Hub-funded research has influenced subsequent technological developments both within and beyond critical materials.

The analysis presented in this report reveals that the CMI Hub has funded patents across a range of critical materials technologies. Recipients of CMI Hub funding have been particularly active in patenting inventions related to technologies such as recycling metals, recovery of lithium and rare earth materials, and advanced aluminum alloys. The CMI Hub’s funding may be helping to fill research gaps in the latter two technology areas, with the leading critical materials companies appearing to decrease focus in these areas.

Citation tracing reveals that, despite CMI Hub-funded patents being relatively recent and thus not having had much time to citated in subsequent generations of technology, there are numerous examples of their influence on downstream innovations. These include innovations within critical materials, such as aluminum alloys and lithium recovery, and also innovations in other technologies, notably in additive manufacturing with specific applications as varied as printing systems, vehicle components, and contact lenses.

Appendix A. Defining the Universe of U.S. Department of Energy-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 the 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, the U.S. Department of Energy (DOE) operates 17 national laboratories. Patents emerging from these laboratories may be assigned to DOE. However, they may also be assigned to the organization that manages a given laboratory. For example, many patents from Sandia National Laboratories are assigned to Lockheed Martin (Sandia National Laboratories' former lab manager), while many Lawrence Berkeley 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 their patents cannot all be defined 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.

1790 Analytics has 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, including:

- DOEPatents Database, a database of DOE-funded patents maintained by DOE's Office of Scientific & Technical Information, 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. The DOEPatents database was accessed in July 2023 for this analysis.
- iEdison Database. DOE's Office of Energy Efficiency and Renewable Energy (EERE) staff provided an output from the iEdison database through April 2019. This database 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.
- Visual Patent Finder Database. EERE also supplied an output from its Visual Patent Finder tool. This tool takes DOE-funded patents and clusters them based on word occurrence patterns. In this case, the output was a flat file containing DOE-funded patents through April 2019.
- Patents assigned to DOE in the USPTO database. There are a small number of U.S. patents issued through June 2023 that are assigned to DOE itself but are not in any of the sources above. These patents were added to the list of DOE patents.
- 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. A search returned all patents that refer to the U.S. Department of Energy or DOE in the Government Interest field, including different variants of these strings. Also identified were patents that refer to government contracts beginning with “DE” or containing the string “ENG.” The former string typically denotes DOE contracts and financial assistance projects, while the latter is a legacy code listed on a number of older DOE-funded patents. A manual check was implemented of all 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 National Science Foundation contracts). All additional DOE-funded patents issued through June 2023 were then added to database.

The all-DOE patent database constructed from these five sources contains more than 36,000 U.S. patents issued between January 1976 and June 2023.

Appendix B. Critical Minerals Innovation Hub-Funded Critical Materials Patents Used in the Analysis

Table B-1. The U.S. Patents Funded by the Critical Materials Innovation Hub Used in This Study's Analysis

Patent Number	Application Year	Issue / Publication Year	Assignee	Title
US9337010	2015	2016	LAWRENCE LIVERMORE NAT SECURITY LLC; GENERAL ELECTRIC	FLUORESCENT LIGHTING WITH ALUMINUM NITRIDE PHOSPHORS
WO2016014110	2015	2016	IOWA STATE UNIV	RECOVERING HEAVY RARE EARTH METALS FROM MAGNET SCRAP
WO2016195831	2016	2016	UT BATTELLE LLC	MEMBRANE ASSISTED SOLVENT EXTRACTION FOR RARE EARTH ELEMENT RECOVERY
US9777346	2015	2017	BATTELLE ENERGY ALLIANCE LLC	METHODS FOR RECOVERING METALS FROM ELECTRONIC WASTE, AND RELATED SYSTEMS
WO2017040031	2016	2017	BATTELLE ENERGY ALLIANCE LLC	METHODS FOR RECOVERING METALS FROM ELECTRONIC WASTE, AND RELATED SYSTEMS
US9691545	2016	2017	LAWRENCE LIVERMORE NAT SECURITY LLC	DEVELOPING BULK EXCHANGE SPRING MAGNETS
US9725788	2015	2017	IOWA STATE UNIV	RECOVERING HEAVY RARE EARTH METALS FROM MAGNET SCRAP
WO2017132285	2017	2017	IOWA STATE UNIV; LAWRENCE LIVERMORE NAT SECURITY LLC; UT BATTELLE LLC	NEODYMIUM-IRON-BORON MAGNET WITH SELECTIVE SURFACE MODIFICATION, AND METHOD OF PRODUCING SAME
WO2017079183	2016	2017	UT BATTELLE LLC	SYSTEM AND METHOD FOR THE RECYCLING OF RARE EARTH MAGNETS

WO2017218900	2017	2017	UT BATTELLE LLC; ECK INDUSTRIES	STRUCTURAL DIRECT-WRITE ADDITIVE MANUFACTURING OF MOLTEN METALS
WO2017007908	2016	2017	UT BATTELLE LLC; ECK INDUSTRIES; LAWRENCE LIVERMORE NAT SECURITY LLC; IOWA STATE UNIV	CASTABLE HIGH-TEMPERATURE CE-MODIFIED AL ALLOYS
WO2017127506	2017	2017	UT BATTELLE LLC; UNIV WASHINGTON STATE	STIMULI-RESPONSIVE LIQUID CRYSTALLINE NETWORKS
WO2018085234	2017	2018	BATTELLE ENERGY ALLIANCE LLC; UNIV OF IDAHO	METHODS OF RECOVERING RARE EARTH ELEMENTS FROM A MATERIAL
US9938628	2015	2018	GENERAL ELECTRIC	COMPOSITE NANOPARTICLES CONTAINING RARE EARTH METAL AND METHODS OF PREPARATION THEREOF
US10029920	2016	2018	IOWA STATE UNIV	SEPARATION OF TERBIUM(III,IV) OXIDE
WO2018022129	2017	2018	IOWA STATE UNIV	SEPARATING RARE EARTH METAL OXALATES
WO2018048464	2017	2018	IOWA STATE UNIV	DISSOLUTION AND SEPARATION OF RARE EARTH METALS
US9968887	2015	2018	UT BATTELLE LLC	MEMBRANE ASSISTED SOLVENT EXTRACTION FOR RARE EARTH ELEMENT RECOVERY
US9963770	2016	2018	UT BATTELLE LLC; ECK INDUSTRIES; LAWRENCE LIVERMORE NAT SECURITY LLC; IOWA STATE UNIV	CASTABLE HIGH-TEMPERATURE CE-MODIFIED AL ALLOYS
WO2018052515	2017	2018	UT BATTELLE LLC; UNIV TENNESSEE; IOWA STATE UNIV; ECK INDUSTRIES	SURFACE-HARDENED ALUMINUM-RACE EARTH ALLOYS AND METHODS OF MAKING THE SAME

WO2018052517	2017	2018	UT BATTELLE LLC; UNIV TENNESSEE; IOWA STATE UNIV; ECK INDUSTRIES	ADDITIVE MANUFACTURING METHODS USING ALUMINUM-RARE EARTH ALLOYS AND PRODUCTS MADE USING SUCH METHODS
US10378081	2017	2019	BATTELLE ENERGY ALLIANCE LLC	METHODS FOR RECOVERING METALS FROM ELECTRONIC WASTE, AND RELATED SYSTEMS
US10196708	2017	2019	LAWRENCE LIVERMORE NAT SECURITY LLC; BATTELLE ENERGY ALLIANCE LLC	ENGINEERED MICROBES FOR RARE EARTH ELEMENT ADSORPTION
US10323299	2016	2019	IOWA STATE UNIV	RECOVERING RARE EARTH METALS FROM MAGNET SCRAP
US10323300	2016	2019	US DEPT ENERGY	PROCESS FOR RECYCLING RARE EARTH MAGNETS
US10266915	2016	2019	UT BATTELLE LLC; ALGER ALTERNATIVE ENERGY LLC	COMPOSITION FOR RECOVERY OF LITHIUM FROM BRINES, AND PROCESS OF USING SAID COMPOSITION
WO2019173716	2019	2019	UT BATTELLE LLC; ALL AMERICAN LITHIUM LLC	LITHIUM EXTRACTION COMPOSITE FOR RECOVERY OF LITHIUM FROM BRINES, AND PROCESS OF USING SAID COMPOSITION
US10253261	2017	2019	UT BATTELLE LLC; UNIV WASHINGTON STATE	STIMULI-RESPONSIVE LIQUID CRYSTALLINE NETWORKS
US10407535	2016	2019	UT BATTELLE LLC; UNIV WASHINGTON STATE	3D PRINTABLE LIQUID CRYSTALLINE ELASTOMERS WITH TUNABLE SHAPE MEMORY BEHAVIOR AND BIO-DERIVED RENDITIONS
US10533239	2016	2020	BATTELLE ENERGY ALLIANCE LLC; UNIV OF IDAHO	METHODS OF RECOVERING RARE EARTH ELEMENTS FROM A MATERIAL
US10760168	2018	2020	GENERAL ELECTRIC	COMPOSITE NANOPARTICLES

				COMPRISING A COMPLEXING LIGAND AND METHODS OF PREPARATION THEREOF
US10648063	2018	2020	IOWA STATE UNIV	DISSOLUTION AND SEPARATION OF RARE EARTH METALS
US10586640	2017	2020	IOWA STATE UNIV; LAWRENCE LIVERMORE NAT SECURITY LLC; UT BATTELLE LLC	NEODYMIUM-IRON-BORON MAGNET WITH SELECTIVE SURFACE MODIFICATION, AND METHOD OF PRODUCING SAME
US10643776	2016	2020	UT BATTELLE LLC	SYSTEM AND METHOD FOR THE RECYCLING OF RARE EARTH MAGNETS
US10689727	2016	2020	UT BATTELLE LLC	METHODS FOR LIQUID EXTRACTION OF RARE EARTH METALS USING IONIC LIQUIDS
US10782193	2017	2020	UT BATTELLE LLC; IOWA STATE UNIV	HIGH COMMAND FIDELITY ELECTROMAGNETICALLY DRIVEN CALORIMETER
WO2020180441	2020	2020	UT BATTELLE LLC; UNIV TENNESSEE; ECK INDUSTRIES; IOWA STATE UNIV; COLORADO SCHOOL OF MINES; LAWRENCE LIVERMORE NAT SECURITY LLC	PRODUCTION OF CASTABLE LIGHT RARE EARTH RICH LIGHT METAL COMPOSITIONS FROM DIRECT REDUCTION PROCESSES
US10584403	2017	2020	UT BATTELLE LLC; UNIV TENNESSEE; IOWA STATE UNIV; ECK INDUSTRIES	SURFACE-HARDENED ALUMINUM-RARE EARTH ALLOYS AND METHODS OF MAKING THE SAME
US10760148	2017	2020	UT BATTELLE LLC; UNIV TENNESSEE; IOWA STATE UNIV; ECK INDUSTRIES	ADDITIVE MANUFACTURING METHODS USING ALUMINUM-RARE EARTH ALLOYS AND PRODUCTS MADE USING SUCH METHODS

US10954585	2019	2021	BATTELLE ENERGY ALLIANCE LLC	METHODS OF RECOVERING RARE EARTH ELEMENTS
US11035023	2019	2021	BATTELLE ENERGY ALLIANCE LLC	REACTOR SYSTEMS FOR RECOVERING METALS, AND RELATED METHODS
US11149356	2017	2021	BATTELLE ENERGY ALLIANCE LLC	METHODS OF FORMING METALS USING IONIC LIQUIDS
US11090579	2019	2021	IOWA STATE UNIV	SEPARATING RARE EARTH METAL OXALATES
US11040296	2019	2021	UT BATTELLE LLC	LIPOPHILIC DIGLYCOLAMIDE COMPOUNDS FOR EXTRACTION OF RARE EARTH METALS FROM AQUEOUS SOLUTIONS
US11186893	2020	2021	UT BATTELLE LLC	RARE EARTH AMIDE COMPOSITIONS
US11230750	2018	2022	LAWRENCE LIVERMORE NAT SECURITY LLC; BATTELLE ENERGY ALLIANCE LLC	ENGINEERED MICROBES FOR RARE EARTH ELEMENT ADSORPTION
US11250980	2020	2022	UT BATTELLE LLC	SYSTEM AND METHOD FOR THE RECYCLING OF RARE EARTH MAGNETS
US11293078	2019	2022	UT BATTELLE LLC	SEPARATION OF RARE EARTH ELEMENTS USING SUPPORTED MEMBRANE SOLVENT EXTRACTION
US11253820	2019	2022	UT BATTELLE LLC; ALL AMERICAN LITHIUM LLC	LITHIUM EXTRACTION COMPOSITE FOR RECOVERY OF LITHIUM FROM BRINES, AND PROCESS OF USING SAID COMPOSITION
US11535912	2021	2022	UT BATTELLE LLC; ECK INDUSTRIES	STRUCTURAL DIRECT-WRITE ADDITIVE MANUFACTURING OF MOLTEN METALS
US11365463	2020	2022	UT BATTELLE LLC; UNIV TENNESSEE; ECK INDUSTRIES; IOWA STATE UNIV; COLORADO	PRODUCTION OF CASTABLE LIGHT RARE EARTH RICH LIGHT METAL COMPOSITIONS FROM DIRECT REDUCTION PROCESSES

			SCHOOL OF MINES; LAWRENCE LIVERMORE NAT SECURITY LLC	
US11491546	2020	2022	UT BATTELLE LLC; UNIV TENNESSEE; IOWA STATE UNIV; ECK INDUSTRIES	ADDITIVE MANUFACTURING METHODS USING ALUMINUM-RARE EARTH ALLOYS AND PRODUCTS MADE USING SUCH METHODS
US11649537	2018	2023	IOWA STATE UNIV	PERMANENT MAGNET ALLOYS FOR GAP MAGNETS
US11611266	2019	2023	UT BATTELLE LLC	AUTOMATED RECOVERY OF RARE EARTH PERMANENT MAGNETS FROM ELECTRIC MACHINES
US11608546	2020	2023	UT BATTELLE LLC; ECK INDUSTRIES; IOWA STATE UNIV; LAWRENCE LIVERMORE NAT SECURITY LLC; UNIV TENNESSEE	ALUMINUM-CERIUM-MANGANESE ALLOY EMBODIMENTS FOR METAL ADDITIVE MANUFACTURING
US11590717	2017	2023	UT BATTELLE LLC; IOWA STATE UNIV	EXTRUDABLE MAGNETIC INK AND NOVEL 3D PRINTING METHOD TO FABRICATE BONDED MAGNETS OF COMPLEX SHAPE
US11565318	2020	2023	UT BATTELLE LLC; UNIV TENNESSEE; ECK INDUSTRIES	REACTIVE MATRIX INFILTRATION OF POWDER PREFORMS

Appendix C. Critical Materials Patent Families Linked via Citations to Earlier Critical Materials Innovation Hub-Funded Critical Materials Patents

Table C-1. Critical Materials Patent Families Linked via Citations to Earlier Critical Materials Innovation Hub-Funded Critical Materials Patents

Family ID	Priority Year	Representative Patent	Issue/Pub Year	Assignee	Title
68983014	2018	WO2019245784	2019	Arconic Inc	Improved aluminum alloy products and methods for making the same
70284676	2018	WO2020081150	2020	Arconic Inc	Aluminum alloys having iron and rare earth elements
62217802	2017	US11185923	2021	Raytheon (Hamilton Sundstrand)	Method of manufacturing aluminum alloy articles
62235821	2017	US11192188	2021	Raytheon (Hamilton Sundstrand)	Method of manufacturing aluminum alloy articles
66949929	2017	US11534748	2022	Standard Lithium	Process for recovery of lithium from brine
67844460	2017	US11518686	2022	Standard Lithium	Process for recovery of lithium from brine
72836952	2019	WO2020211304	2020	Chinese Academy of Science	Method for grouping and separating yttrium oxide from high-yttrium rare earth ore and method for grouping and separating yttrium oxide from middle-yttrium europium-rich rare earth ore
77771315	2020	WO2021188227	2021	Dow Chemical Co (Rohm & Haas); Univ California	Preparation of cerium (iii) carbonate dispersion
87575591	2023	US11732326	2023	Extractive Metallurgy Consultants	Extraction of lithium from mudstone and sequestration of carbon dioxide
73288526	2020	EP4232192	2023	GeoLith	Composite material and process for extracting lithium using the same
66248015	2017	US11229880	2022	Intl Battery Metals	Modular extraction apparatus
65229684	2017	US11408056	2022	Intelligent Composites	Aluminum based alloy containing cerium and graphite

86057773	2021	WO2023065044	2023	PH7 Tech	Solvents and methods for leaching precious metals
69404947	2018	US11426818	2022	State Univ of New York	Additive manufacturing processes and additively manufactured products
85323167	2021	WO2023027911	2023	University of Chicago	Pre-seeding lithium in one-dimensional olivine hosts for lithium extraction

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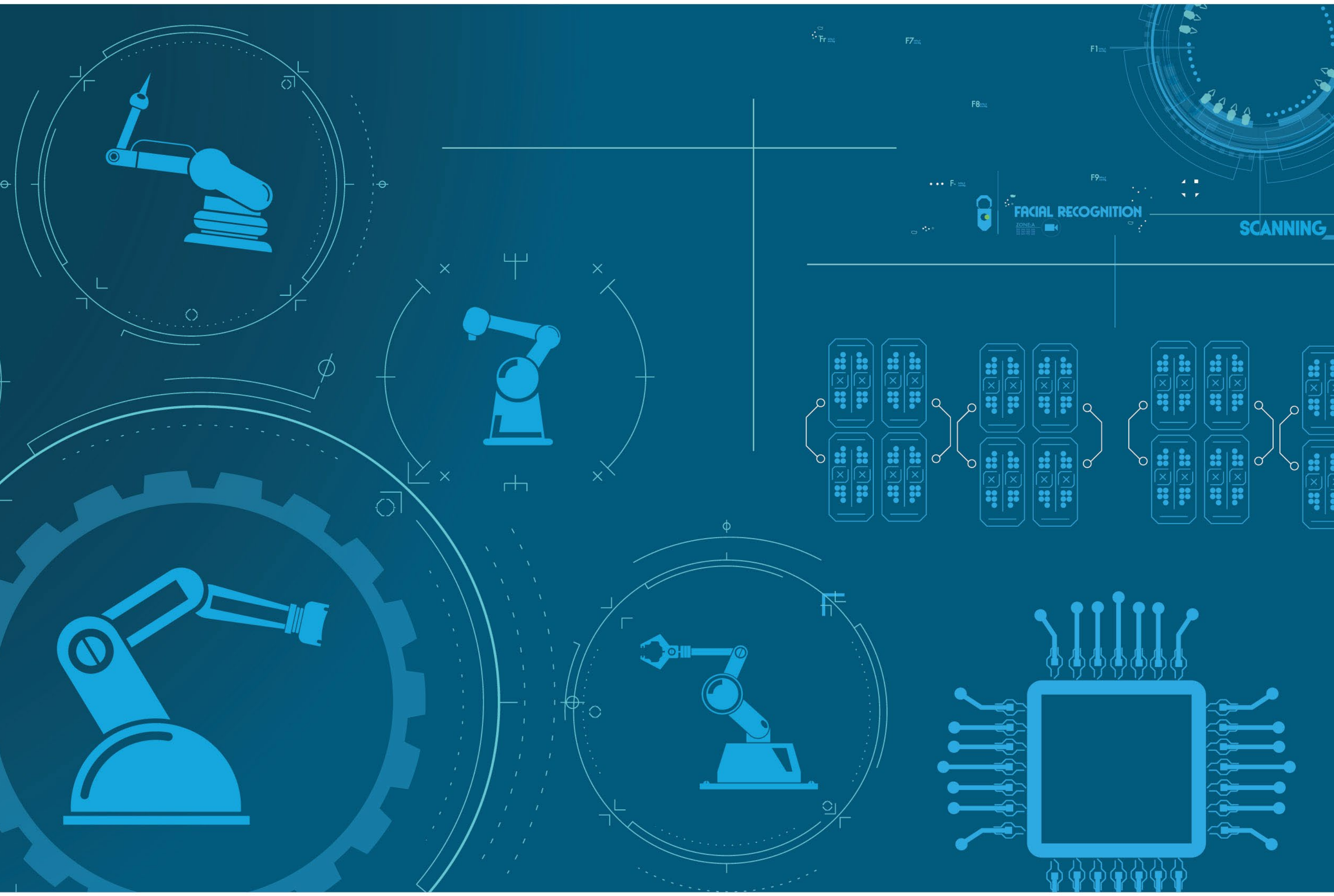

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