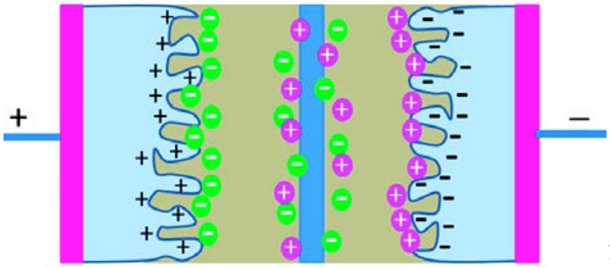
Office of the Assistant Secretary of Defense: Research & Engineering (OASD(R&E))

TECHSIGHT SNAPSHOT REPORT

AUGUST 2017

Office of Net Technical Assessments (ONTA)

Supercapacitors



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Executive Summary

Supercapacitors have been rapidly emerging over the past decade as a viable technology to bridge the gap between electrolytic capacitors and rechargeable batteries with the capacity to store and rapidly charge & discharge large amounts of energy. They have the potential for game-changing effects in pulsed power, directed energy, unmanned vehicles and many other areas. The emergence of supercapacitors is largely driven out of the material sciences and chemistry communities with a recent focus on using graphene and other carbon allotropes, such as carbon nanotubes and activated carbon, to build them. Publications on supercapacitors jumped an order of magnitude over the past decade, from around 500 articles in 2006 to over 5000 articles in 2016, with much of that growth occurring in the past 4 years. This work is highly cited, with an average of 20 citations per article. Patenting activity also grew steadily and doubled over the past decade, primarily in the fields related to energy storage and its use in the automotive sector. China is the top producer of supercapacitor research by a factor of almost 4, relative to its nearest competitor, the United States, and outperforms the U.S. in citations by 60%. China is also the second top producer of supercapacitor patents, producing a little more than half of the top producer, Japan. While today's supercapacitors have strong commercial interest in the automotive sector, they are nowhere near their theoretical limits, and their rapid improvements in the future may unlock other potential applications.

[1] Graphic element is derived from (Chen & Dai, 2014)

I. Introduction to Snapshot Reports

Snapshot reports provide a short overview of recent activity in emerging and potentially disruptive research areas using quantitative metrics generated from the statistical analysis of publication trends in the scientific and patent literature exclusively using ONTA's TechSight System. The aim of these reports is to generate questions for deeper investigations, and they are engineered to be produced monthly in a rapid, timely fashion with figures automatically generated by TechSight. Since these figures are inserted from a dynamic interface, readers are encouraged to access this data on TechSight for further exploration. TechSight is available to all DoD personnel and contractors (*see APPENDIX for access instructions*). Future snapshot reports will analyze top organizations and entities as system improvements to TechSight such as entity disambiguation is implemented.

II. What are Supercapacitors?

Supercapacitors are electrical components that have the features of both batteries and capacitors and are often described to "bridge the gap between electrolytic capacitors and rechargeable batteries." For example, they "typically store 10 to 100 times more energy per unit volume or mass than electrolytic capacitors, can accept and deliver charge much faster and tolerate many more charge and discharge cycles than rechargeable batteries." Thus, supercapacitors excel in "applications where a large amount of power is needed for a relatively short time, where a very high number of charge/discharge cycles, or a longer lifetime is required." They are also called "supercaps, ultracapacitors, Goldcaps, or electric double-layer capacitors (EDLC)." (Wikipedia, n.d.)".

Supercapacitors store charge through a very different mechanism than today's high-performance batteries, which is the origin of their ability to deliver and accept large amounts of power. "The electrochemical processes occurring in batteries and supercapacitors give rise to their different charge-storage properties. In lithium ion (Li+) batteries, the insertion of Li+ that enables redox reactions in bulk electrode materials is diffusion-controlled and can be slow. Supercapacitor devices, also known as electrical double-layer capacitors (EDLCs), store charge by adsorption of electrolyte ions onto the surface of electrode materials. No redox reactions are required, so the response to changes in potential without diffusion limitations is rapid and leads to high power. (Simon, Gogotsi, & Dunn, 2014)"

Today's supercapacitors still have a long way to go before they are able to replace batteries in their primary role as an energy storage component. "The major challenge for electrochemical supercapacitors, when compared to both batteries and fuel cells, is their insufficient energy density which cannot fully meet the growing demand of the applications where high energy density is required. To overcome this challenge, extensive work has been devoted to increase the energy density of electrochemical supercapacitors in order to widen their application scope. Since the energy density of electrochemical supercapacitors is proportional to the capacitance and the square of the voltage, increasing either or both of the capacitance and the cell voltage is an effective way to increase the energy density. This can be achieved through the development of electrode materials with high capacitance, electrolytes with wide potential windows, and integrated systems with a new and optimized structure. (Zhong, et al., 2015)"

The development and application of new materials, particularly graphene, holds the promise for tomorrow's supercapacitors reaching the same energy density as batteries. "Graphene has attracted great interest for supercapacitors because of its extraordinarily high surface area. Owing to its remarkable quantum capacitance and excellent electrical and mechanical properties, calculations show that graphene has the potential to help realize supercapacitors with the energy density of batteries that can be recharged in seconds. In practice, the energy density of graphene supercapacitors achieved so far is far below the theoretical values. (El-Kady, Shao, & Kaner, 2016)"

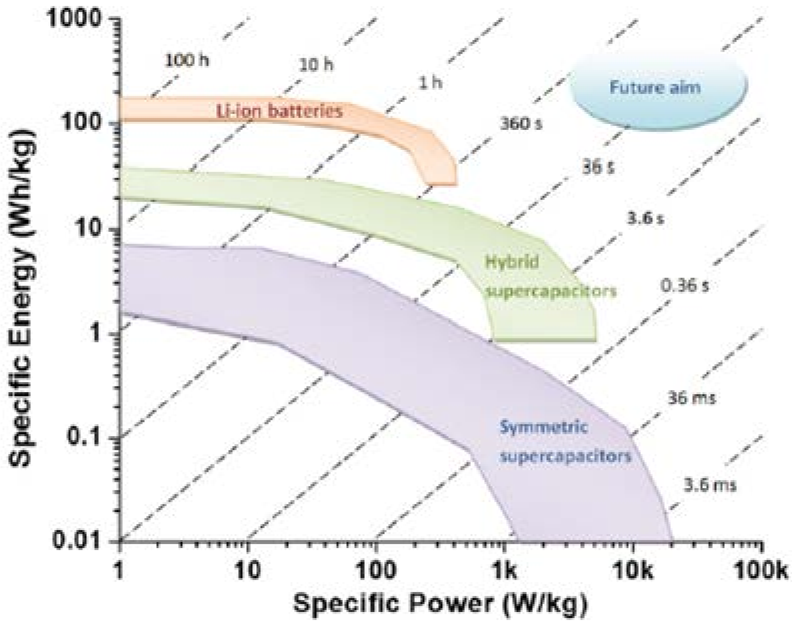

Figure 1: Ragone plot of energy density vs. power density for batteries and different types of today's supercapacitors. These describe different varieties of supercapacitors and the future aim of the field: to achieve parity in energy density with high-performance batteries. Figure derived from (Tiruye, 2014)

III. What is the Research Landscape?

Top Research Disciplines: Materials Science and Chemistry

- *Prevalence of materials-related terminology suggests that most of the innovations occur at the material level, rather than at the device or system levels.*

Top Research Topics: Carbon-Based Materials

- *The top keyword is **graphene**, indicating that a large amount of supercapacitor research in the materials area focuses on this material, as well as other carbon allotropes such as **carbon nanotubes** and **activated carbon**, which are also mentioned at high frequency.*
- *Carbon-based materials are used with less frequency in the patent literature, possibly indicating that the use of these new materials have not yet fully transitioned from R&D to applications.*

Top Application Areas: Energy Storage

- ***Energy and Fuels** listed as a top-ranked subject category, with particular focus on their use in automobiles (**electric vehicles** and **automatic electrics** patent classifications).*

Research fields comprise different thrusts and self-organization of articles often occurs around key questions and drivers in the field. The semantic content of the technical language, namely the technical terms, is typically a good indicator for tracking this activity. Similarly, how this research populates curated hierarchical subject categories can indicate what disciplines influence and dominate the field as well as other fields where this research has been influential. To extract the research field of interest, the following Boolean query was used:

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supercapacitor OR ultracapacitor OR "electric double layer capacitor" OR pseudo-capacitor

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Top Publication Keywords

Rank	Keywords	Counts	Citations
1	supercapacitor	6,701	171,121
2	graphen	1,302	44,777
3	energi storag	954	28,571
4	carbon nanotub	762	26,416
5	polyanilin	639	17,003
6	activ carbon	632	18,652
7	electrochem capacitor	605	22,475
8	electrochem properti	556	15,135
9	nanocomposit	548	11,205
10	composit	434	13,557

Top Patent Terms

Rank	Term	Counts	Citations
1	electric	5,735	36,025
2	capacitor	5,263	28,983
3	layer	4,983	27,649
4	electrode	4,532	26,052
5	double	4,043	20,077
6	material	3,397	20,236
7	comprise	2,921	29,654
8	battery	2,559	20,483
9	device	2,549	25,125
10	carbon	2,433	14,626

Top Publication Subjects

Rank	Subject	Counts	Citations
1	materials science, multidisciplinary	10,717	369,128
2	chemistry, physical	7,496	321,729
3	electrochemistry	5,827	149,313
4	chemistry, multidisciplinary	4,978	212,094
5	energy & fuels	4,327	122,520
6	nanoscience & nanotechnology	3,884	172,835
7	physics, applied	3,737	144,273
8	engineering, electrical & electronic	2,636	21,803
9	physics, condensed matter	2,238	112,189
10	engineering, chemical	845	27,341

Top Patent Classifications

Rank	Classification	Counts	Citations
1	(l) electro-(in)organic	8,156	50,697
2	(v) resistors and capacitors	6,908	39,141
3	(x) electrochemical storage	6,860	47,719
4	(a) electrical applications	3,903	26,623
5	(x) electric vehicles	1,624	11,153
6	(e) non-metallic elements, semi-metals (se, te, b, si) and their compounds	1,213	8,380
7	(x) automotive electrics	854	7,517
8	(t) digital computers	811	10,545
9	(x) power distribution/components/converters	723	7,735
10	(u) amplifiers and low power supplies	694	6,487

Figure 2 These figures are derived from a search query performed to define the supercapacitors field. **(Top, Left)** Shows the popular keywords used in Web of Science. **(Top, Right)** Shows the popular terms used in the title section of patents in the Derwent Patent Index. **(Bottom, Left)** Shows the subject categories used in Web of Science. **(Bottom, Right)** Shows the patent classification keywords used in the Derwent Patent Index.

IV. How Mature is the Field?

ONTA estimates that Supercapacitors are rapidly maturing with a large footprint in both research and innovation. It bases this judgment on the factors below.

Size: Large

- *The field is relatively large with ~25,000 publications and ~12,000 patents.*

Growth: Rapid

- *Though research extends long before the 1990s, the field has been experiencing exponential-like growth.*

Influence: High

- *Publications in this field average about 20 citations per paper*
- *Patents average about 10 citations per filing.*

Maturity: Developed

- *The high ratio of patents to publications indicates a high level of transition from basic research to real-world applications.*

	Publications	Patents
Document Counts	24,899	12,071
Citations	637,432	118,027
Authors/Inventors	35,338	

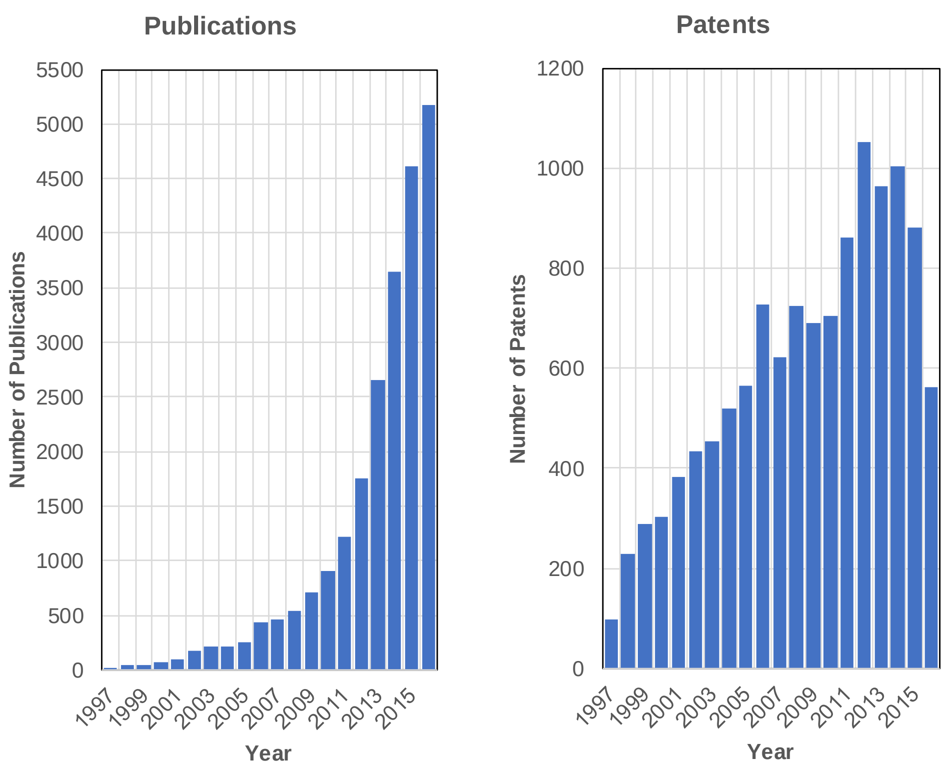

Figure 3 (Top, Left) Shows the *document counts, author counts and citation counts* for Supercapacitors in the

Web of Science. These fields correlate to *accumulated knowledge, workforce size and influence/quality*, respectively. **(Top Right)** Shows the *patent counts and citation counts* for the field of Supercapacitors in the Derwent Patent Index. **(Bottom Left)** Shows the number of articles and conference proceedings mentioning Supercapacitors in the title or abstract per year of publication. **(Bottom Right)** Shows the number of patents mentioning Supercapacitors in the title or abstract per year of publication. The current year has been omitted since not all the publications for this year have been indexed.

V. What are the Leading Countries?

Top Research Producer: China

- ***China*** *is the top producer of academic research, and exceeds its nearest competitor, the U.S. by a factor of 4.*
- ***China*** *has the most research citations, 60% more than its closest competitor, the U.S.*

Top Innovator: Japan

- ***Japan*** *produces the most patents of any country, nearly doubling its closest competitor, China.*
- *The* ***U.S.*** *has the most number of patent citations, nearly doubling its closest competitor, Japan.*

Top Market for Innovation: Japan

- *Nearly twice as many patents are filed in* ***Japan*** *as its next closest competitor, the U.S. However, the most patents cited were filed with the* ***U.S.*** *Patent Office.*
- *The high ratio of patents to publications indicates a high level of transition from basic research to real-world applications.*

Overall, while China displays an overwhelming lead in the total volume of research produced, this has not translated into similar gains in the patent space. The U.S. remains competitive, but does not lead in any particular area, securing either 2nd or 3rd place across the board. Other strong countries include South Korea (#3 in articles, #4 in patents) and France (#6 in articles, #5 in patents) while India is strong in articles (#4) but unusually weak in patents (#10).

The country affiliation of articles and patents are inferred through the mailing address. These broadly indicate a country's contribution and expertise. Additionally, we can also analyze the patent-granting authority, which is often associated with a country and indicates where an innovation area has the most protection and coverage.

Top Countries by Publication

Rank	Country	Articles	Citations
1	china	11,437	265,280
2	united states	3,633	166,483
3	south korea	2,153	50,351
4	india	1,748	28,342
5	japan	1,342	31,609
6	france	913	48,116
7	singapore	823	48,917
8	australia	765	27,537
9	germany	739	22,516
10	united kingdom	674	22,706

Top Countries by Patents

Country	Patents	Citations
japan	4,311	44,297
china	2,321	9,863
united states	2,023	78,187
south korea	630	3,144
france	252	1,664
germany	194	2,086
taiwan	158	1,305
canada	94	1,961
united kingdom	75	1,494
india	58	951

Top Patent-Granting Offices

Office	Patents	Citations
japan	7,408	81,916
united states	3,910	105,944
china	3,847	62,034
world intellectual property organization	2,798	61,281
european patent office	1,799	68,328
south korea	1,720	24,426
taiwan	636	9,854
germany	477	13,445
canada	460	30,132
india	451	35,364

Figure 4 Shows the top countries and in Supercapacitors based on: **(Left)** the country affiliation of the authors in the Web of Science, **(Middle)** the country affiliation of the assignee from the Derwent Patent Index, **(Right)** the patent granting authority (typically a country) from the Derwent Patent Index.

VI. Questions for Further Study

Snapshot reports are meant to be quick scans of S&T and to ultimately stimulate interesting questions using only statistical data from the S&T literature. Answering these questions requires other methods, including interviewing stakeholders and experts.

International Competition

- *General Electric and Standard Oil, two U.S. companies, were responsible for the initial discoveries in Supercapacitors (Wikipedia, n.d.). Why is the US now lagging in patent and publication output in the area of supercapacitors?*
- *Does Japan's heavy interest in supercapacitor driven by their automotive manufacturing industry?*
- *Are there topical differences in the research between different countries?*
- *Who are the leaders in specific research thrusts?*

Technology Advancements

- *What is the role of graphene and other carbon allotropes in supercapacitors? Why are they a key driver in supercapacitor research?*
- *Supercapacitors were discovered in the early 1950s (Wikipedia, n.d.). Is their recent natural exponential growth originate from that period, or has there been a more recent development that the growth can be traced back to?*
- *Is graphene research responsible for the increased growth in patents that started around 2009?*

Impacts

- *Are there other applications outside of energy storage where supercapacitors could be used? For example, current research is focused on energy density, a battery-like characteristic, while little research focuses on power density and breakdown voltage, key characteristics of capacitors.*

VII. Further Reading (Most Cited Work)

Rank	Citations	Article Title	Source	Year
1	6,242	Materials for electrochemical capacitors	NATURE MATERIALS	2008
2	4,663	Nanostructured materials for advanced energy conversion and storage devices	NATURE MATERIALS	2005
3	4,000	Graphene-Based Ultracapacitors	NANO LETTERS	2008
4	2,764	What are batteries, fuel cells, and supercapacitors?	CHEMICAL REVIEWS	2004
5	2,602	Preparation and characterization of graphene oxide paper	NATURE	2007
6	2,507	A review of electrode materials for electrochemical supercapacitors	CHEMICAL SOCIETY REVIEWS	2012
7	2,367	Carbon materials for the electrochemical storage of energy in capacitors	CARBON	2001
8	2,324	Carbon-Based Supercapacitors Produced by Activation of Graphene	SCIENCE	2011
9	2,318	Principles and applications of electrochemical capacitors	ELECTROCHIMICA ACTA	2000
10	2,147	Carbon-based materials as supercapacitor electrodes	CHEMICAL SOCIETY REVIEWS	2009

Rank	Citations	Patent Title	Assignee	Year
1	678	Surgical instrument e.g. surgical stapler instrument, endoscope, laparoscopic instrument, cutting instrument has memory device in communication with first sensor and is configured to record output of sensor, while sensor has output	JOHNSON & JOHNSON, ETHICON ENDO-SURGERY INC	2006
2	665	Hybrid energy system for managing the storage and transfer of electrical energy produced by diesel-electric locomotives, such as excess prime mover power and dynamic braking energy	GENERAL ELECTRIC CO	2001
3	573	Lighting fixture for use in e.g. public environment, has processor for selecting power supply source to be utilized based on output of algorithm in accordance with rule stored in memory of processor	DIGITAL LUMENS INC	2008
4	556	Yarn production method involves drawing from pre-primary assembly to provide primary assembly of nanofibers having alignment axis about which twisting can occur	UNIV TEXAS SYSTEM, COMMONWEALTH SCI & IND RES ORG	2004
5	478	Motor e.g. stepper motor, driven surgical cutting and fastening instrument i.e. endoscopic instrument, for use by e.g. physician for endoscopic application, has motor with operational modes for portions of cutting stroke cycle of instrument	ETHICON CORP, ETHICON ENDO-SURGERY INC	2008
6	466	Surgical stapler i.e. endocutter, for use by surgeon, has curved portion defined by radius of curvature, and linear portion defining axis that is not parallel to or collinear with shaft axis	ETHICON ENDO-SURGERY INC	2007
7	466	Status module has individual contact which is structured and arranged in electrical communication with different sensor when housing is connected to pneumatically powered surgical instrument	ETHICON ENDO-SURGERY INC	2007
8	458	End effector assembly for use with surgical stapler, has several connectors arranged within openings of piece of buttress material and apertures of staple cartridge deck and anvil face, to retain buttress material to cartridge and anvil	ETHICON ENDO-SURGERY INC	2008
9	454	Staples catridge for use in endoscopic and/or laparoscopic surgical technique, has two cavities defining in body, where each cavities are configured to receive two staples respectively, and each cavities includes two ends	ETHICON ENDO-SURGERY INC	2,0
10	421	Surgical stapling and severing instrument for medical application, has electroactive polymer actuator that is biased into locking contact with control actuator in initial position to prevent movement of control actuator to next position	JOHNSON & JOHNSON, ETHICON ENDO-SURGERY INC	2004

Figure 5 The following list shows **(Top)** the most cited articles in the supercapacitors field from the Web of Science and **(Bottom)** most cited patents from the Derwent Patent Index.

VIII. About this Publication

Referenced work in this publication does not constitute endorsement by the United States Department of Defense (DoD) of the linked web sites, nor the information, products or services contained therein. In addition, the content featured does not necessarily reflect DoD's views or priorities. To provide feedback or ask questions, contact us at asdre-st-bulletin-reply@sainc.com. This publication is authored and distributed by:

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X. APPENDIX

A. Scientometric Methodology

TechSight is an open-resource, cloud-based ecosystem developed and maintained by ONTA. As of this writing, it consists of an ElasticSearch database infrastructure with a Kibana front-end and some commercial and custom-written plugins. The databases used for this analysis were global scientific publications using the Web of Science and global patent applications using the Derwent Patent Index, both provided by Clarivate, Inc. All of the figures generated in this report come from visualizations generated by Techsight.

More dashboards for this specific report are available on the ONTA TechSight system and contain additional visualization elements not included in this report since their dynamic nature is not compatible with static reporting. These include network visualizations that allow for a finer-grained analysis and allow the user to delve into specific information on top performing universities, companies, authors and inventors. To access it, sign up for a free account at:

https://registration.761link.net/accountRequest-ZoneB/accountRequest/techsight.

You must be either a DoD employee, or a contractor supporting DoD, and register using your .mil e-mail address.

A search query is manually developed by an analyst to capture best capture the field of this report. Development of this query is directed at improving precision (by eliminating non-relevant documents from the results) and recall (by collecting as many relevant documents as possible) through the use of Boolean operators and unique terms. Since ElasticSearch is being used, differences in term suffixes are automatically accounted for and require no additional specification.

B. How large is a research field or area of innovation? (Frequency Analysis)

The size of a research field can be estimated in terms of total aggregated knowledge, for which the metric cumulative document counts is a suitable proxy. Under the assumption that every article is unique and therefore constitutes a single unit of knowledge, then sum of all the articles in a research field approximates the total knowledge accumulated in the field. Another suitable metric is total community size, for which the number of unique authors is a suitable metric since these are the workers that generate knowledge. A larger workforce tends to correlate to a greater capacity to produce knowledge and therefore grows proportionately with aggregated knowledge. Some fields exhibit differing productivity (i.e. documents per unique worker) depending on ease of publishing, difficulty in carrying out experiments and field-dependent variables. Fields like particle physics and clinical medicine tend to have articles with a large number of authors due to the difficulty of the experiments. Fields such as nanoscience and nanotechnology tend to have higher productivity due to the ease of publishing new results. Fields like mathematics tend to have only a single author due to the nature of the work, and fields in computer science tend to have generally low publication rates relative to their research production. Similar factors affect patent indicators and are notably shaped by key differences between the two corpora, such as motivations for publishing versus patenting, the differences between peer review and patent examination, and the choice of technical terminology. Field sizes and influence are based on analyst observations and experience in a semi-quantitative rough order of magnitude sense: very small fields <10 articles, small fields <100 articles, medium fields <1,000 articles, large fields <10,000 articles, very large fields >100,000 articles. For influence: poorly cited <1 citation/article, medium citation rate ~1 citation/article, high citation rate >10 citations/article.

C. How influential is a research field? (Citation Analysis)

Scientific articles contain a list of references that cite previously published articles. The number of times an article has been referenced by other articles is called its citation count. Over time, an article's citation count tends to increase as subsequently published articles cite that article. Citation count tends to correlate with an article's influence, indicating the article's content has influenced other articles. Citation is also a suitable proxy for quality, as more articles describing the first reports of original work tend to have higher citations. An exception to this rule are review articles which tend to have very large citation counts and contain no original work but are cited typically to point new readers to a compact source for their further education in the field. Despite this exception, it is not inappropriate to include review articles in a citation analysis because they articles tend to be more widely read, and are a demand signal that a field has aggregated enough knowledge that a convenient repository for that knowledge is desirable. Since citation counts provide a usable proxy for "quality", this analysis provides a counterbalance to the "quantity" metric of document counts.

D. How fast is the research field or area of innovation growing? (Trend Analysis)

Scientific fields grow over time as researchers publish related articles, building on early seminal works. Emerging and potentially disruptive research areas typically display rapid, exponential-like growth early early in their lifecycle.

E. What are the key areas of research, development and innovation? (Semantic Analysis)

The content of a research field can be understood from a hierarchical framework. Understanding the parentage of the field creates awareness of the nature and character of the field relative to the context of current scientific organization. As a proxy, we use the Web of Science's Subject Categories field, which are inspired by OECD's Field of Science (FOS) categories (OECD Cateogry Scheme, n.d.). While a field tends to localize around a specific section of this hierarchy, outliers sometimes exist arising from relevant articles in unrelated research fields indicating this field has influenced work or been adopted by these other fields. Similarly, patents in the Derwent Patent Index (DWPI Classification System, n.d.) are inspired by the WIPO classification and section scheme and lend themselves to similar visualization schemes. Research topics can often be conceptually subdivided into sub-topics. These sub-topics are often differentiated by specific keywords which are indicative of the content of these subtopics and represent segments of research focusing on research drivers such as key questions or specific innovations. Quantitatively tracking these keywords indicates the relative popularity of these sub-topics.

F. What are the leading countries? (Country Cross-Analysis)

Authors and inventors are affiliated with organizations whose addresses are in specific countries. By subdividing the data according to country, we can produce analyses at the national level that broadly indicate a country's participation level in a research field. Top 10 Countries by Publications are determined by the address of the affiliation of the author in the Web of Science. Note that an author can have multiple affiliations, thus belong to multiple countries. Top 10 Countries by Patent Application are determined by the address of the affiliation of the assignee in the Derwent Patent Index. An alternative approach is to use the inventor affiliation, which results in larger country counts since a patent can have multiple inventors, but only one assignee. Patent protection can be granted by applying to nation-specific authorities (i.e. U.S. Patent and Trademark Office), regional authorities (i.e. European Patent Office) or international authorities (World Intellectual Property Oganization). It is often useful to compare which countries patents in a specific technology are granted and comparing that to where those companies are affiliated as it indicates whether one country is seeking IP protection in another country, or worldwide, for its products.