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Tracing the ultracapacitor commercialization pathway

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A B S T R A C T

Ultracapacitors have been under development for over two decades and recently have received attention for their commercial applications in products such as hybrid electric vehicles, medical devices, grid energy storage, and personal electronics. Ultracapacitors are attractive for their ability to quickly deliver large quantities of power, making them an ideal complement to battery technology in comprehensive power systems. Recent technical advancements have developed ultracapacitors with performance that is now viable in a variety of commercial applications. This research uses publication, patent and investment data to identify and trace the commercial pathway for this emerging technology. The firms and industries currently developing and commercializing ultracapacitors are identified using affiliation data. To date, ultracapacitor R&D has been primarily performed by large multinational companies with broad energy-based product portfolios and emerging venture-backed capacitor companies. Firms in industries including transportation, consumer electronics, and medical equipment have researched how ultracapacitors can be integrated into power systems. The early stages of ultracapacitor development are compared with Li-ion and NiMH batteries and evidence shows similarities between the early stages of the commercially successful Li-ion battery.

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1. Introduction

While dozens of new energy storage technologies are emerging from laboratories every year, only a subset will be transferred into commercially available products. One technology of particular interest is the ultracapacitor. Ultracapacitors offer the ability to quickly deliver large quantities of power, making them a potentially attractive and ideal complement to battery technology. When paired with traditional batteries, they can offer peak and backup power to create more robust energy systems. Ultracapacitors have been under development for over two decades and recently have received attention for their commercial applications in products such as hybrid electric vehicles, medical devices, grid energy storage, and personal electronics [1–4].

This paper traces the pathway of development and commercialization of ultracapacitors. We use publications and patents, the outputs of R&D, to identify the firms that have lead the development of ultracapacitors and those that are adopting the technology in their product lines. This bibliometric data is paired with investment data to develop a robust picture of the commercialization process for this emerging energy storage technology.

Section 2 details the advantages offered by ultracapacitor technologies and the applications that have been considered in the literature. Section 3 explains the publication and patent data used to determine industrial involvement in the development of ultracapacitor technologies and identify the firms leading the research and commercialization of the technology. Section 4 interprets the bibliometric data and investment figures to profile the firms that are bringing ultracapacitors to market. Section 5 examines the evolution of ultracapacitor adoption in downstream industries such as transportation, consumer electronics, and medical devices. Finally, we compare the current trajectory of ultracapacitors with more advanced and mature energy storage technologies: lithium-ion (Li-ion) and nickel metal hydride (NiMH) batteries. We use these trajectories to forecast the commercialization potential for ultracapacitors.

2. Ultracapacitor technology

2.1. Technology description

After two decades of research, ultracapacitors are emerging as a commercially promising energy storage technology. Rechargeable battery technologies are currently the most common form of energy storage making them the closest direct competitor of ultracapacitors. Batteries store energy using chemical reactions. When the battery is charged or discharged, the ions move from the solution and are embedded into the structure of the electrodes. Capacitors use electrostatic storage compared to the battery's chemical storage. The electrodes are commonly made of porous carbon. When ultracapacitors are charged, the ions cling to the surface to the electrode instead of implanting. This key difference results in two performance advantages for ultracapacitors. It takes less time for an ion to electrostatically cling, therefore ultracapacitors have a faster charge and discharge time than rechargeable batteries. In addition, the repeated ion implantation in rechargeable batteries results in the eventual degradation of the electrode and ultimate battery failure. As a result, ultracapacitors have longer lifetimes and increased reliability.

To date, the key obstacle to the adoption of ultracapacitor technologies are the technical performance challenges of low capacitance and low voltage windows. These limit the amount of energy that can be stored. The materials that are currently used, including electrodes and electrolytes, typically only provide for a maximum energy density of approximately 5–7 Wh per kg of material. Compared to a lithium ion battery, however, the same amount of material would store 25 times more energy, but take longer to charge. Recent advancements in nanomaterials engineering have developed electrolytes and electrodes that have dramatically improved the performance of ultracapacitors now making them a commercially viable technology. Thanks to these technical advances, ultracapacitors now have higher energy efficiency than Li-ion batteries (92% vs. 85%), higher power, and longer life cycles [2]. Ultracapacitors are now becoming commercially viable in a range of applications and it is projected that from 2016 to 2021 the global consumption value of lithium ion capacitors will increase 80% per year, reaching over $150 million by 2021 [5].

2.2. Ultracapacitor applications

Renewable energy sources, like wind and solar, offer enormous potential for meeting future energy demands. Global investment in renewable energy was $257 billion in 2011 [6]. Of this, $231 billion were investments in the areas of solar and wind. One key obstacle to the adoption of these technologies is the inability to efficiently store the power generated at off peak times. Power grids are only capable of accepting constant frequencies of current at specific times. For residential and commercial grid applications, electricity must be reliable; even second-to-second fluctuations in frequency can cause major disruptions and stresses to the power grid. Rather than taking solar panels or wind turbines off the grid when production is too high, the producer could store the excess energy for periods when production is low and demand is high. Electrical energy storage systems are critical for effectively leveling the cyclic nature of these energy sources. Ultracapacitors are particularly attractive in this application due to their faster charge and discharge time. They are better designed to respond to second-to-second fluctuations than rechargeable batteries.

More efficient energy storage systems are also critical to the widespread adoption of hybrid/electric vehicles. These vehicles capture the energy from braking, store it briefly as electricity, and apply it to accelerate the car without using fossil fuels. Batteries are not efficient for the relatively rapid charge and discharge cycles so hybrid/electric vehicles frequently must rely on the gasoline engines when accelerating quickly. Electric vehicles add batteries in order to get adequate power resulting in redundancy and additional weight. Ultracapacitors are ideal complements to Li-ion batteries in vehicle power systems. They can capture more of the braking energy and quickly discharge large amounts of power required for acceleration thus lowering the need for fossil fuel sources and battery redundancy [7]. Analyses of the hybrid/electric vehicle market project that global annual sales will reach 2.1 million units in 2013 and 3.8 million units by 2020 [8,9]. Supporting data from Toyota shows that 2012 sales of the Prius totaled 247,230 units, which at the suggested retail price of $24,000, accounted for revenues of $5.93 billion. Combined with higher government fuel efficiency standards and increasing gas prices, the hybrid/electric vehicle market is poised for substantial growth over the long term. To meet these higher demands and more rigorous performance requirements, ultracapacitors will need to be adopted in hybrid/electric vehicle power systems.

The military is also exploring ultracapacitors as an energy storage technology due to the extreme operating environments. From 2006 to 2010, the military spent over $2.1 billion on fuel cell, battery, and capacitor power sources, including procurement, R&D, and logistics [10]. The military needs high reliability energy storage devices to start vehicle engines quickly, conserve on fuel, and enhance off-the-grid operability for troops in forward operating zones. Overheating Li-ion batteries, such as the ones that grounded the new Boeing 787 Dreamliner jet, would be very dangerous in the presence of munitions. Ultracapacitors have longer lifecycles and have a wider temperature window making them ideal for extreme conditions.

While these applications of ultracapacitors have been identified in the technical literature, to date there has been no analysis of whether these applications are being pursued. We will now examine ultracapacitor-related research outputs to gain insights into which of these or other applications are currently under development. This will allow us to see the commercialization pathways ultracapacitors are following into the marketplace.

3. Data

3.1. Data sources and methods

To better understand the development of an emerging technology such as ultracapacitors, we need to understand who is investing in the technology and their potential motivations for doing so. This information can be difficult to track because there is no uniformly collected data on investments being made in the development of these technologies. We use three different data sources to construct a picture of the ultracapacitor horizon. Publication and patent data identify the firms pursuing ultracapacitor technology. This data is paired with investment reports to get a better sense of the new ventures created to commercialize ultracapacitor technologies.

3.2. Publication data

Peer-reviewed journal publications represent the outputs of basic research in electrochemical capacitors. The Elsevier SciVerse Scopus database compiles the articles published from over 20,000 journals and conference proceedings worldwide. The Scopus database was searched to identify trends in ultracapacitor research. The search term “ultracapacitor” OR “supercapacitor” was used to identify the relevant articles published in scientific journals. Publication and affiliation data were mined to identify trends in capacitor research.

The first paper related to ultracapacitors was published in 1977 and there were a handful of research articles in the 1980s. Consistent publication of research did not begin until 1991. Publishing has grown at an average annual rate of 34% over the past decade and 39% since 1991 (Fig. 2). The author affiliation data provides insights into who is performing the research on ultracapacitors. Over 22% of papers have an author located in China. The US has the second largest share with 20%. Other major international players include France (8%), South Korea (8%), and India (6%).

The vast majority of the published research is coming from researchers in universities. Only 241 of the 3199 papers in the database have at least one author affiliated with a company. This is not uncommon as academics are encouraged to research and publish findings in peer-reviewed journals. Firms are far more likely to focus research efforts on later stage product development and protect their discoveries through patents or retain them as trade secrets.

3.3. Patent data

Patents are the primary bibliometric output of later stage research with commercial applications. The US Patent and Trademark Office's database of awarded patents were searched for all patents that include the terms “ultracapacitor” OR “supercapacitor”. This search yields all patents that protect technologies related to the design or production of ultracapacitors. It also includes all technologies whose descriptions specify ultracapacitors as a power source. These patents represent an application of the new technology rather than an advancement of the technology. Since 1990, 775 patents have been awarded for the development or application of ultracapacitors. There has been an average annual growth rate in patenting of 24% (Fig. 3).

Each patent has been assigned to an entity who controls the intellectual property rights associated with the patent. The assignee data can provide information on which entities are funding later stage commercial research. 84% of all ultracapacitor patents have been assigned to companies and 8% of the patents have been awarded to universities. This data shows a reversal of the trends in publication where 8% of publications were authored by industrial researchers. All industrial patents were then linked with data on the assignee companies.

3.4. Firm and investment data

The firm and investment data provides insight into how aggressively companies and investors are pursuing the development and commercialization of ultracapacitors relative to other clean energy and energy storage technologies. We looked at the industry leading firms, large and small, in the energy storage space that have invested in capacitors as well as the general investment trends of the clean energy and energy storage industries.

The energy storage market has been one of the only bright spots in clean energy for institutional investors, including venture capitalists, angels, and private equity in recent years. US venture capital investment in clean energy companies increased by 73% to $1.1 billion in Q3 2011 compared to Q3 2010. The energy storage segment led all clean energy investment sectors during Q3 2011. This segment raised $421.0 million during Q3 2011, representing a 1932% increase during the same period last year and raised a total of $865.2 million through Q3 2011 [6]. As institutional investors remain bearish on solar and biofuels, they continue to pour hundreds of millions of dollars in the energy storage space. Furthermore, strategic corporate venture capitalists including Dow Chemical Company, Maxwell Technologies, General Electric, Siemens, and others are also investing hundreds of millions in companies that are developing energy storage technologies like capacitors (Fig. 1).

4. Trends in technology development

Investment and firm data was sourced from Securities and Exchange Commission databases, market reports, financial information registries, and company websites and official press releases. These three data sets were used to identify trends in ultracapacitor development. Publication author affiliation and patent assignee data was cross referenced with company databases to assign an industry classification to each patent. This provides insight into the industrial sectors investing in the development of ultracapacitors. We were able to assign an industry sector to 219 of the 241 industrial publications and 180 of the 217 industrial patents in our dataset. The distribution of publications and patents is shown in Fig. 4.

The largest portion of publications, the output of earlier stage research, on the development of ultracapacitors has been performed by firms classified in the electronic capacitor industry. Companies working to develop and test their capacitor technologies accounted for over one third of basic research. The next largest segments of earlier stage research were electrical (18%) and transportation equipment (12%). These are industries that will rely on ultracapacitor technologies and may be researching them in their earliest stages to prepare for adoption. Scientific and technical services also had a significant proportion in both publications (8%) and patenting (10%). These companies included start-up

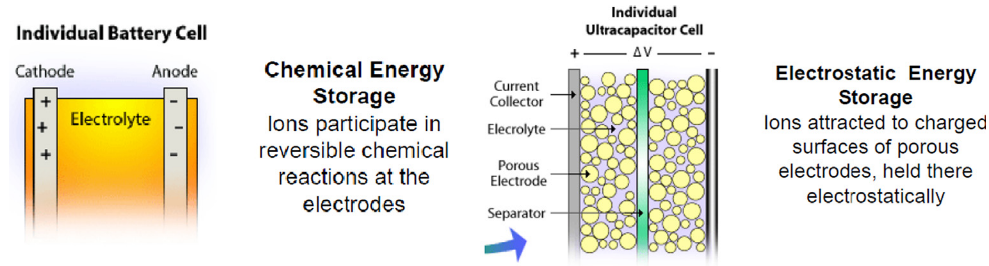

Fig. 1. Rechargeable Batteries and Ultracapacitors.
Source: NREL

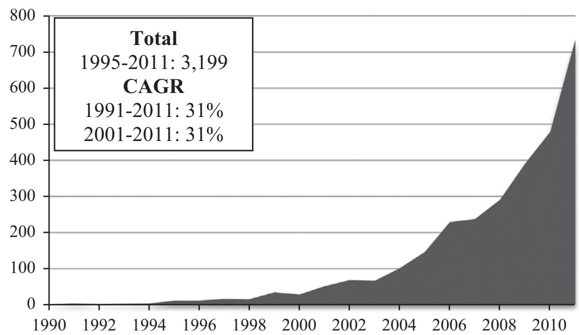

Fig. 2. Annual ultracapacitor research publications.

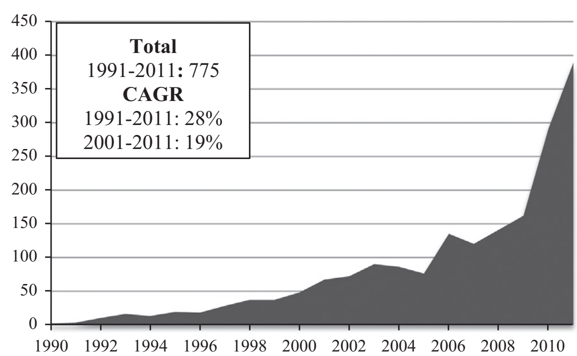

Fig. 3. Annual ultracapacitor patents (USPTO).

companies in the early stages for which the primary output is research before they have commercialized a product and energy engineering firms who view ultracapacitors as critical components for the systems they are designing Fig. 5.

Patenting trends show the firms that are developing ultracapacitor technologies and those that are developing applications. Companies developing ultracapacitors only account for 11% of all of the patents. Chemical manufacturing is also a large patenter (9%) focusing on the development of chemical solutions that will enable higher performance in ultracapacitors. The bulk of the remaining applications are for technologies that will use ultracapacitors as a power source. Almost one-fifth of ultracapacitor patents have been awarded to the transportation equipment industry and another 15% were for consumer electronics. The electrical and medical equipment industries account for an additional 19% of the awarded patents. This suggests that industrial research is being done to adopt these new power sources in order to enable the development of new downstream technologies. This information now allows us to focus on trends in the development of ultracapacitors and the research being performed in order to commercialize and adopt the technologies.

4.1. Ultracapacitor development

Several large multinational conglomerates are actively involved in developing and commercializing various types of ultracapacitors. The leading players globally include Hitachi, LG Chem, NEC-Tokin, Panasonic, and Siemens, all of which have an established reputation in the energy storage market. Given the size of these companies and diversification of the technologies in their development pipelines and product lines, it is nearly impossible to decipher investment and revenue data specifically for their ultracapacitor efforts. These players represent the most likely acquirers and joint development partners of best-in-class ultracapacitor specialty and start-up companies.

A123 Systems, which had a market capitalization of over $2B just a few years ago, is best known for its advanced lithium iron phosphate batteries and energy storage systems. With $159M in annual revenues in 2011 and over $500M in investments, A123 represented one of the highest profile and best known clean energy companies in the world. They were primarily focused on their battery business; however, they had an internal R&D group that actively researches and develops advanced capacitors and other technologies. Their recent bankruptcy filing and subsequent sale to Wanxiang Group, China's largest automobile parts company, leaves A123 future ultracapacitor development efforts in question.

CAP-XX is an Australian ultracapacitor company that makes thin, prismatic ultracapacitors. Founded in 1997, CAP-XX targets the commercial, wireless, and consumer electronics markets. This represents a significantly different market focus than most other ultracapacitor specialty and start-up companies. The company has raised over $27M since inception, but only generated about $3.5M in revenue in 2011.

EEStor is a notoriously mysterious energy storage start-up that is said to be building a ultracapacitor material that would store more energy and charge and discharge faster than previous materials by a factor of ten. The company has long been criticized for overpromising and under delivering on its commercialization roadmap. Kleiner Perkins Caufield and Byers, one of the top three cleantech venture capital firms in the world, invested $3M in EEStor in 2005, but does not list the company in their portfolio.

FastCAP Systems is a publicly (Department of Energy ARPA-E and Massachusetts Clean Energy Center) and angel-funded early stage Massachusetts Institute of Technology spinout company. Founded in 2008, FastCAP Systems is focused on tapping into the growing hybrid electric vehicle market with its proprietary carbon nanotube electrode technology. The company has only recently started selling its commercial products to customers.

Ioxus, widely regarded as one of the world's top pure-play capacitor companies, develops and sells a range of ultracapacitor products. With over $34M in investment from traditional equity investors and strategic partners, including GE, NRG Energy, and ConocoPhillips, Ioxus is focused on ultracapacitor solutions for the hybrid automotive, hybrid bus, wind turbine pitch control, UPS,

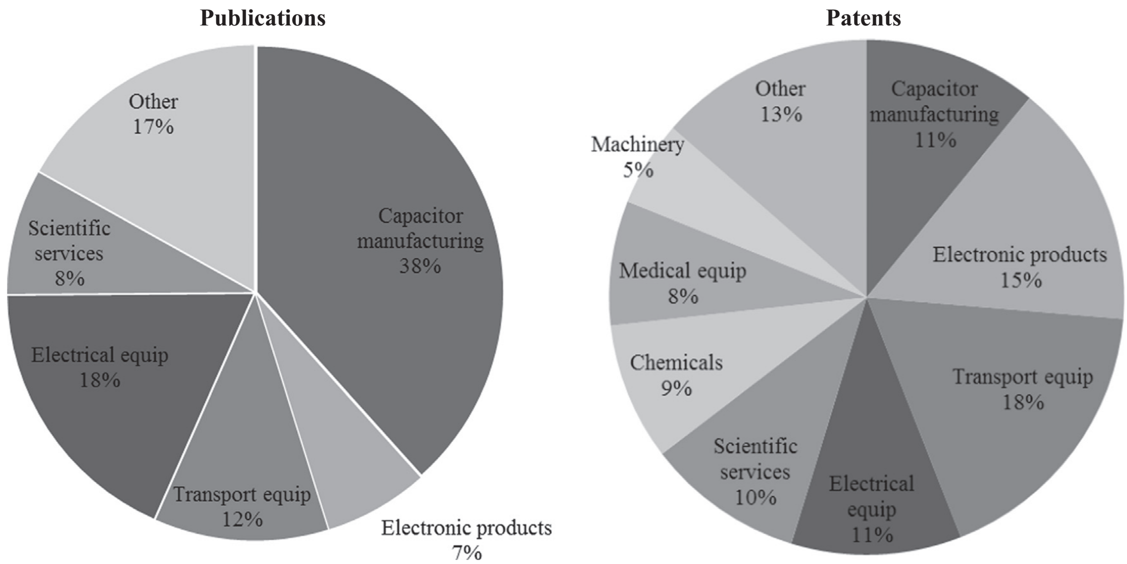

Fig. 4. Industrial ultracapacitor publication and patenting by industry.

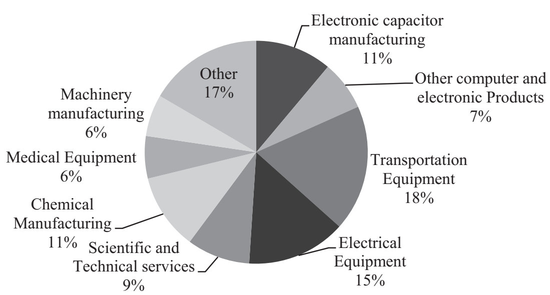

Fig. 5. Industrial ultracapacitor patenting by industry.

and industrial markets. Ioxus does not disclose sales figures for any of the offerings in its line of products.

Maxwell Technologies, another leader in the global capacitor market, designs, sells, and distributes ultracapacitors for a range of applications including transportation, power generation, and data centers. Founded in 1965 as Maxwell Laboratories, Maxwell Technologies changed its name in 1996. Maxwell Technologies boasts annual revenues of over $157M and is in much better financial health than its closest competitor, A123 Systems. There is no initial investment data available on the company.

Nesscap is a global ultracapacitor company that focuses on the consumer, industrial and automotive market segments. The company's main operations and production facilities are based in South Korea. A heavy concentration of its customers are based in South Korea and the rest of Asia, however, Nesscap sells its products to companies around the world. Founded in 1998, Nesscap has raised $37.5M in investments since inception. Nesscap's 2011 annual revenue was almost $18M.

4.2. Potential suppliers

Over a dozen companies in the chemicals industry have been awarded patents for ultracapacitor development. Many of these firms including, Hyperion Catalysis, Cabot Corporation, and Intermolecular are developing materials that can be used as inputs into cutting edge ultracapacitors. These firms have developed new anodes, cathodes, and electrolyte solutions that can be used to make more efficient energy storage devices.

Table 1
Small and Medium Ultracapacitor Companies.
Sources: 1—SciVerse Scopus, 2—patft.uspto.gov, 3—www.sec.gov/edgar/searchedgar/companysearch.html, 4—www.cap-xx.com, 5—www.greentechmedia.com, 6—www.crunchbase.com and gigacom.com/cleantech, 7—www.nesscap.com.

Company	Publications[1]	Patents[2]	Year founded	Investments[3] (in millions $)	Revenues[3] (in millions $)
A123 Systems	0	0	2001	$ 503.0	$ 159.1
CAP-XX	7	7	1997	$ 27.3[4]	$ 3.5
EEStor	0	0	2001	$ 13.1[5]	NA
FastCAP Systems	0	0	2008	$ 9.2	NA
Ioxus	4	1	2007	$ 34.5[6]	NA
Maxwell Technologies	34	5	1965	NA	$ 157.3
Nesscap	0	4	1998	$ 37.5[7]	$ 18.0

4.3. Batteries and fuel cells

Multiple companies focused on other energy storage systems have been awarded patents involving ultracapacitors. Fuel cell companies Ballard and Altergy have over a dozen patents. Battery companies such as Duracell and Rayovac have both patents and publications related to the development ultracapacitors. It is possible that these firms are using their existing expertise in power storage to enter a new product line. They may also be looking to incorporate ultracapacitor performance in their power management systems. Companies focused on electric power generation and distribution such as Hydro Quebec, have also been researching and developing ultracapacitors.

5. Ultracapacitor applications

5.1. Personal electronics

Cell phone and telecommunications equipment manufacturers have invested in the development ultracapacitor related devices. Firms in this industry accounted for 8% of the publications and 15% of patents. One of the major patent holders is Research in Motion (15),

Table 2
Publication summary statistics.

	Li-ion	NiMH	Ultracapacitor
Date of first publication	1969	1969	1977
Years to first 100 publications	20	25	25
Mean annual growth rate (1995–2011)	23%	7%	34%
Max annual growth (1995–2011)	58%	77%	100%
Min annual growth (1995–2011)	−14%	−41%	−25%
Std dev growth rates	18%	35%	33%

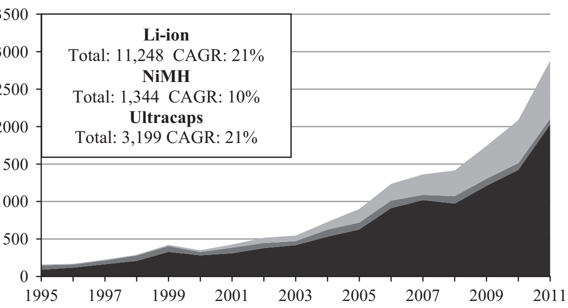

Fig. 6. Annual publications.

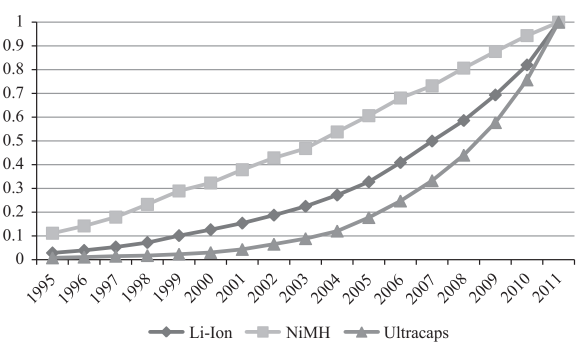

Fig. 7. Cumulative distribution of publications.

Table 3
Patent Summary Statistics.

	Li-ion	NiMH	Ultracapacitor
Date of first patent	1976	1988	1984
Years to first 100 patents	13	8	14
Mean annual growth rate (1995–2011)	27%	24%	25%
Max annual growth (1995–2011)	74%	170%	80%
Min annual growth (1995–2011)	−10%	−17%	−12%
Std dev growth rates	27%	41%	29%

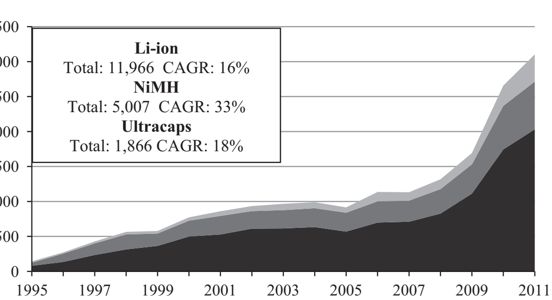

Fig. 8. Patent trends.

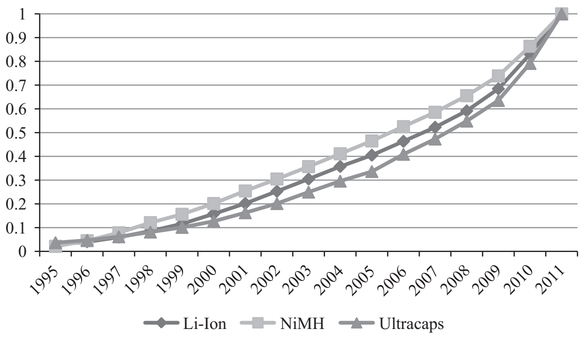

Fig. 9. Cumulative distribution of patents.

the company responsible for the Blackberry. Other cell phone manufacturers with patents and publications are Motorola, Qualcomm, and Samsung. Semiconductor manufacturers have also invested in the development of ultracapacitors. Their chips are critical to the advancements of personal electronics devices. There are also investments from other companies such as Powermat that have developed wireless chargers for personal electronics. Other electronics multinationals such as General Electrics, Philips, Sony, and Honeywell have all done research in ultracapacitors that will likely support multiple products in their portfolios.

5.2. Transportation

Transportation is considered the most likely first application for ultracapacitors. Ultracapacitors have been recognized for their potential role in power management systems of hybrid and electric vehicles. Ultracapacitors can discharge a great deal of power immediately that would provide these vehicles with immediate pick up when the driver steps on the accelerator. Automotive companies are among the top publishers and patenters for ultracapacitor technology. Researchers at General Motors, Ford, and other automotive and parts manufacturers have published 20 papers relating to the development of ultracapacitors. These industries were also responsible for 86 patents. Major automotive manufacturers developing ultracapacitor based technologies include GM, Ford, Diamler, Hondo, Hyundai, Peugeot, and Volvo. Tesla, a manufacturer of high end electric vehicles, is also developing capacitor technologies. Automotive part manufacturers are also investing in technologies that will utilize capacitors and have been awarded 32 patents through the end of 2011. Also included in this category are manufacturers of heavy duty equipment such as Caterpillar and Oshkosh.

5.3. Medical equipment

Medical equipment manufacturers have invested in the development of products that utilize the unique properties offered by ultracapacitors. These include the development of hearing aids, coclear implants, diabetes monitoring systems, pacemakers, pain control devices, and other medical devices. All of these devices require reliable power management and the advancement of ultracapacitor technologies could enable new and improved features in these downstream industries. In total, these companies accounted for 38 or 21% of the classified patents. The major developers of these technologies were Advanced Bionics Corporation, Merck, and Boston Scientific.

6. Comparison with lithium-ion batteries and nickel metal hydride

The power density and quick discharge time of ultracapacitors show great potential for multiple applications. However, it can be difficult to interpret the patent and publication data without a baseline for comparison. We examine the bibliometric data associated with two recently developed energy storage technologies: lithium-ion and nickel metal hydride batteries (Table 1).

Table 2 provides summary statistics on the publication data collected for all three energy storage technologies and Fig. 6 shows the annual number of publications for each of the storage technologies. Published research on battery technology began appearing in 1969. Research on ultracapacitors first appeared in 1977, trailing the battery technologies by almost a decade. Emerging energy technologies require a long tail of development to build an initial stock of research. Li-ion batteries achieved 100 publications after 20 years of research, compared to NiMH batteries and ultracapacitors which each required 25 years.

Because these are time series with upward trends, a comparison of growth rates is the most informative. Both Li-ion batteries and ultracapacitors have grown at a compound annual rate of 21% since the publication of their first patents. This is twice as fast as the growth of NiMH battery research. An examination of annual growth rates reveals a great deal of year-to-year volatility in the upward trend. The most stable growth has been in the most established of the technologies, Li-ion batteries. The mean annual growth rate is 23% with a standard deviation of 18%. Ultracapacitors have a much higher average annual growth rate of 34% but a much wider range of annual growth. Fig. 7 shows the cumulative distribution of publications since for each technology. NiMH publications have grown at a constant rate since 1995, while Li-ion and ultracapacitors have grown at much faster rates, particularly since 2000. The similar shapes suggest that ultracapacitor research is more likely following the development path of li-ion technologies.

Patent data can provide more insight into the commercialization of the new technology. Table 3 lists summary statistics related to patent trends and Fig. 8 shows annual patent activity. Li-ion batteries were the first technology to show commercial promise patented almost a decade before NiMH batteries and ultracapacitors.

The patenting of NiMH batteries (33%) has grown at a much faster compound annual growth rate than Li-ion batteries (16%) and ultracapacitors (16%) NiMH batteries also had a much faster launch taking only 8 years to accumulate its first 100 patents. While there is wide variety in compound annual growth rates the mean of annual growth rates are all approximately 25%. NiMH battery development has been far more volatile as can be seen by the standard deviation of 41% compared with Li-ion (27%) and ultracapacitors (29%). The cumulative distribution plot in Fig. 9 shows how closely related the growth of the three technologies has been over the past 15 years.

Correlations between publication and patent activity can also provide some insight into the commercialization pathways. The correlation between publication and patent activity within each of the technologies is very strong: ultracapacitors (0.973), Li-ion batteries (0.973) and NiMH batteries (0.860). However the development of ultracapacitors seems to correlate more strongly with li-ion than with NiMH batteries. The correlations between the publication (0.975) and patenting (0.986) trends of the two technologies is very strong. The coefficients are not nearly as strong when comparing ultracapacitor and NiMH publications (0.648). The correlation coefficients suggest the development of ultracapacitor research and commercialization is more likely to resemble the development of Li-ion batteries than NiMH Table 4.

In practice, ultracapacitors will be used in conjunction with various types of batteries to develop robust power systems. Ultracapacitors will provide bursts of high quantities of energy while batteries will provide lower levels of sustained power. Complete power systems such as those designed for electric vehicles will require both. The USPTO patent database was searched to identify the co-development of technologies using the search terms such as "li-ion battery" AND "ultracapacitor OR supercapacitor" to identify patented technologies that utilize multiple energy storage technologies. Fig. 10, shows the co-development trends of the energy storage technologies. One-fifth (21%) of all ultracapacitor patents awarded represented joint applications of ultracapacitors and Li-ion batteries. Only 7% of ultracapacitor patents included NiMH battery technology. This suggests that ultracapacitors are more likely to be co-developed and adopted with Li-ion battery technologies.

Table 4
Correlation table.

	Ultracap papers	Ultracap patents	Li-Ion papers	Li-ion patents	NiMH papers	NiMH patents
Ultracap papers	–	0.973	0.975	0.950	0.648	0.902
Ultracap patents	0.973	–	0.977	0.986	0.716	0.953
Li-ion papers	0.975	0.977	–	0.973	0.773	0.955
Li-ion patents	0.950	0.986	0.973	–	0.779	0.984
NiMH papers	0.648	0.716	0.779	0.779	–	0.860
NiMH patents	0.902	0.953	0.955	0.984	0.860	–

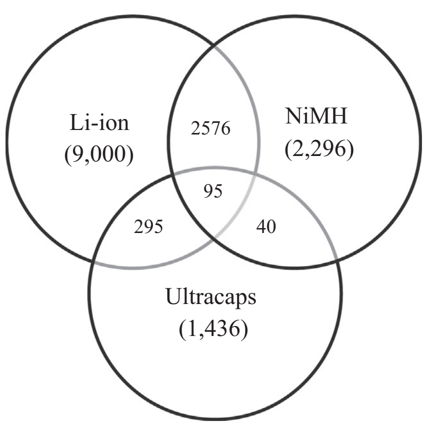

Fig. 10. Co-development of energy storage technologies.

Table 5
Early-stage patenting of energy storage technologies.

Technology	Li-ion	NiMH	Ultracapacitor
# of Assignees	40	43	39
% of industrial assignees	79%	86%	59%
Top 3 industries	Electrical equipment (25%) Computer and electronics (19%) Chemicals (11%)	Computer and electronics (46%) Electrical equipment (29%) Chemicals (2%)	Electrical equipment (16%) Computer and electronics (15%) Chemicals (6%)
Top assignees	General Electric (12)	Motorola (17)	University of California (12), Motorola (10)

Finally, we can compare the early commercial development of the three technologies to gain insights into how ultracapacitors compare. We looked at the first 100 patents awarded for Li-ion and NiMH batteries and ultracapacitors to identify early state technology development trends. Table 5 below summarizes the results.

The early patenting of ultracapacitor technologies shares some similarities with predecessor battery technologies. The first 100 patents were awarded to roughly the same number of assignees. This shows that for the most part development efforts of all three technologies were distributed across a wide range of entities. Ultracapacitor development has been less concentrated in the industrial sector than the two battery technologies. Over 40% of the early patents were awarded to universities, government agencies, and nonprofits. In fact, the most frequent patenter of the emerging technology was the University of California. This may reflect a change in policy. The Bayh Dole Act was adopted in 1982, which gave universities the right to patent and commercialize the outputs of federally funded technologies. Universities would not have had the authority or incentive to patent discoveries related to the two earlier technologies.

The electrical equipment industry, which includes batteries and ultracapacitor manufacturers, was the most prolific inventors of both Li-ion and ultracapacitor technologies. These patents supported the development of the emerging technology. Almost half of the NiMH battery patents were awarded to firms in the computer and electronics industry. These firms, led by Motorola, Toshiba, and PC manufacturers, were interested in developing new battery technologies to support their product lines. A smaller portion of patents were awarded to chemical companies for the advancements of battery and ultracapacitor components.

When comparing the early stages of battery storage technology development, it appears that the commercialization path of ultracapacitors is tracking closely with Li-ion batteries. This bodes well for the potential widespread adoption of ultracapacitors as Li-ion batteries are an integral energy storage technology for a variety of industries and countless applications.

7. Conclusions

The goal of this work has been to use patent, publication, and investment data to map the commercialization pathway of ultracapacitor technologies. The data suggests that ultracapacitor R&D has been primarily performed by large multinational companies with broad energy-based product portfolios and emerging venture-backed capacitor companies. Energy storage has been a growth area for venture capital investment as investments in other clean energy technologies have decreased significantly. This suggests that firms commercializing ultracapacitors will benefit from the continued support of investors. Analysis of patents and publications show that applications of ultracapacitors are also under development. Firms in industries including transportation, consumer electronics, and medical equipment have researched how ultracapacitors can be integrated into relevant power systems.

The early stage development of ultracapacitors closely tracks the initial commercialization pathway of Li-ion batteries. If these patterns continue, we would expect the continued annual growth of patenting at over 20% and heavy adoption of ultracapacitors in electronics. In addition, we believe that co-development of Li-ion batteries and ultracapacitors will continue to become more prevalent. This will enable the development and commercialization of power systems built upon the complementary strengths of these two technologies.

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