Applied Energy 137 (2015) 537–544

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Monitoring innovation in electrochemical energy storage technologies: A patent-based approach

Simon C. Mueller *, Philipp G. Sandner, Isabell M. Welpe

TUM School of Management, Technische Universität München, Arcisstrasse 21, D-80333 Munich, Germany

HIGHLIGHTS

- Grid effects of intermittent sources show increasing need for decentralized storage.
- Novel patent classification is applied to monitor competing technologies.
- Up-to-date geographical, organizational, and qualitative insight is given.
- Redox flow patenting shows strong growth, lithium also strong absolute numbers.
- Revealed patents allow the expectation of improved modules in the future.

ARTICLE INFO

Article history:
Received 28 February 2014
Received in revised form 5 June 2014
Accepted 30 June 2014
Available online 28 July 2014

Keywords:
Electrochemical energy storage
Battery
Patent
Lithium
Regenerative fuel cell
Alkaline

ABSTRACT

Due to the suitability to balance the intermittency in decentralized systems with renewable sources, electrochemical energy storage possibilities have been analyzed in several studies, all highlighting the need for improvements in relevant techno-economic parameters. Particularly a reduction in the costs per cycle is much needed, which could either come from innovation in more cost-efficient manufacturing methods, a higher endurance of charge/discharge sequences or higher capacities. Looking at patent applications as a metric allows us to determine whether the necessary technological progress is indeed occurring, as the mandatory publication of the underlying inventions provides access to otherwise hidden R&D activities. Our paper contributes to the literature with a compilation of technological classes related to important battery types in the novel Cooperative Patent Classification (CPC), which can be used to identify relevant patent applications of the competing technologies. Using the worldwide patent statistical database (PATSTAT), we find that promising technologies have been showing increasing patent counts in recent years. For example, the number of patent applications related to regenerative fuel cells (e.g. redox flow batteries) doubled from 2009 to 2011. Nevertheless, the volume of patent filings in technologies related to lithium remains unchallenged. Patent applications in this area are still growing, which indicates that the introduction of improved modules will continue. Using citation analysis, we have identified important patents and organizations for relevant candidate technologies. Our study underlines that electrochemical storage, and in particular lithium-based technologies, will play an increasingly important role in future energy systems.

1. Introduction

1.1. The importance of innovation research in energy storage technologies

The diffusion of intermittent renewable energy sources reveals the lack of appropriate decentralized energy storage solutions for grid support and residential applications. The effects of intermittent energy sources start to become visible on a national scale for countries with high penetration of renewable energies. While increasingly frequent periods of negative electricity prices [1], caused by temporary oversupply, may only seem bizarre, it underlines the importance of energy storage to prevent inverse events of electricity shortage, which could jeopardize grid stability. Due to the suitability for the desired decentralized structure, electrochemical energy storage possibilities have been analyzed in several studies, all highlighting the need for improvements in relevant techno-economic parameters [2–6].

* Corresponding author. Tel.: +49 89 289 24829.
E-mail address: simon.mueller@tum.de (S.C. Mueller).

http://dx.doi.org/10.1016/j.apenergy.2014.06.082
0306-2619/© 2014 The Authors. Published by Elsevier Ltd.

To support the much-needed progress, understanding innovation in electrochemical energy storage revealed in patents is an important research, as well as public policy, issue for several reasons: firstly, as the economic potential for further improvements is tremendous, it is likely that novel ideas are first patented before scientifically published, if at all. Consequently, it is likely that important know-how concerning batteries is revealed in patents. Secondly, policy-makers considering financial support for energy storage need to have information on the innovative performance in their respective jurisdictions, as this is essential for a well-informed decision about optional technology push or market pull subsidies. The same is true for venture capitalists and capital markets, which are important to bring products from initial R&D to product development. Thirdly, grid designers and (renewable) energy scenario researchers need to know, whether and which, electrochemical energy storage systems could dominate markets in the future. Moreover, the scholarly literature on innovation in energy storage has, up to this point, only encompassed technologies relevant for electric mobility registered at the United States Patent and Trademark Office (USPTO) [7]. Further research drawing a global, organizational and qualitative perspective including technologies relevant for stationary energy storage is therefore a pressing need as "energy storage is very much the key to unlocking the door of renewable energy" [5].

1.2. Electrochemical energy storage technologies

Over the past few decades, differences in supply and demand in electricity grids have already had to be matched. To store the excess capacity at night and ensure availability during high consumption hours, energy has been stored in the gravitational potential using hydropower plants for many decades. Storing significant amounts of energy, however, requires large facilities which have a strong impact on the local environment. Furthermore, not all countries have the geographical profile to build pumped hydro storage plants [6].

Following the transition in the energy generation technology, a structural change from a centralized to a more decentralized system architecture has also been initiated by the introduction of feed-in tariffs. Production of energy at the location of consumption reduces the necessity of electricity transmission through grids. As transmission costs can comprise up to a third of present-day consumer electricity fees, a decentralized system architecture has economically significant advantages. The financial support by feed-in tariffs worldwide has led to a rapid increase in installed renewable energy capacities. This has caused new record values for renewable energy generation, such as for example more than 73% of the national supply on May 11, 2014 in Germany [8,9]. Fig. 1(b) shows the total German energy production and consumption series for a week including a record day in 2013. On June 16, 2013, where renewable energy accounted for 60% of the power, wind energy contributed with approximately 9 GW and photovoltaics with 20 GW. With spot prices assuming negative values, it becomes apparent that already at the present renewable ratios, matching supply and demand becomes increasingly difficult. Next to just meeting demand and supply, it has also been pointed out that power quality becomes a problematic topic with increasing shares of renewables [10].

When analyzing the size distribution of registered renewable energy plants in Germany as shown in Fig. 1(a), it can be seen that all categories – from small kW sized to large MW sized plants – contribute substantially to the overall capacity. Thus, also small- to mid-scale storage systems are needed. Due to their high modularity, electrochemical energy storage in batteries is an important alternative to mechanical and other technologies, such as superconducting magnetic storage, for example.

In the 90s, alkaline, NiCd and NiMH batteries were very common among secondary cells [2]. With the advent of mobile electronics, they entered many households in flashlights, wireless phones and other devices. By combining several thousand cells, a MW ranging energy storage project had already been realized in 2003 (e.g. [11]). Due to the maturity of the technology, NiCd and NiMH secondary cells are therefore candidates which remain to be monitored.

In starter batteries of internal combustion engine vehicles, lead-acid batteries are widespread and have gained broad market diffusion. In China for example, lead-acid batteries have had the greatest share in usage for PV/wind systems. This can be explained by their maturity and cost competitiveness [17].

Increasing requirements in energy density by consumer electronics due to the advent of laptops and smartphones have caused the widespread use of lithium batteries. Next to their high density [20], also the high efficiency of more than 90% [4] renders lithium batteries a promising technology.

Redox flow batteries represent an interesting novel approach to storing larger quantities of energy electrochemically. Due to the in principle high number of cycles, cost competitiveness could be achieved. Also, the storage tanks have very good scalability, rendering flow batteries ideal for larger quantities [4].

Yet another possibility, which is relevant particularly for grid-scale application, is sodium-sulfur batteries, operating at high temperatures. The suitability for large powers, the high efficiency on

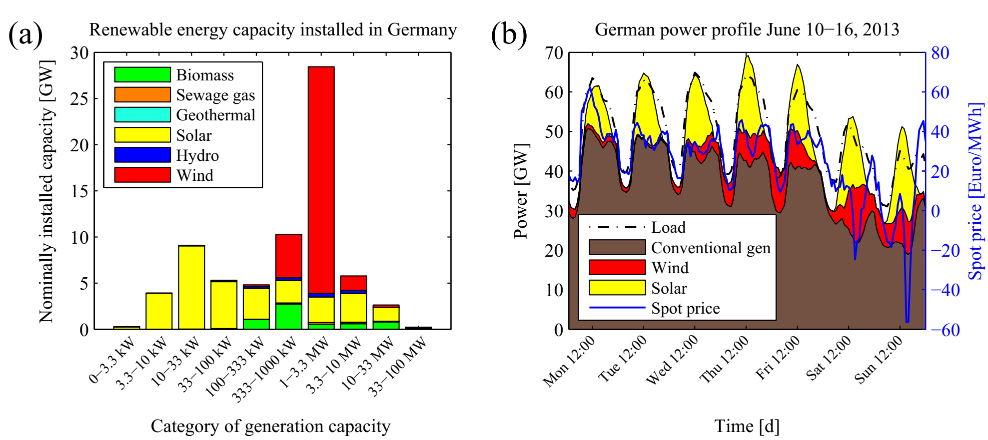

Fig. 1. (a) Installed renewable energy generation capacity per nominal power of individual plant in Germany as of December 31, 2012 (data from [12]). It is apparent that small systems contribute substantially to the overall generation capacity, showing the high degree of decentralization. (b) Overall German power profile showing negative spot market prices on a Sunday with low demand and record renewable energy values (depiction following [13], data sources: load [14], production [15], spot prices [16]).

Table 1
Important techno-economic parameters of investigated technologies (data for 1st, 3rd, 4th, and 5th row taken from [18]; 2nd row values stem from average values for NiCd from [19]).

Technology	Capacity costs (€/kW h)	Cycles	Efficiency (%)
Lithium	844	10,250	90
Alkaline, NiMH, NiCd	600	1500	73
Lead-acid	171	1250	82
Sodium-sulfur	256	3333	81
Redox-flow batteries	398	13,000	75

short timescales, as well as a high number of total cycles before failure, renders them attractive for utility scale load leveling applications. A serious fire event [4,21] has, however, resulted in a sudden decrease in interest.

Of crucial importance for the profitability in applications are the battery costs per cycle [22]. Table 1 shows typical values which have been obtained from previous literature [18,19]. One of the first applications where battery operation is expected to become financially attractive are so-called island or micro grids. In such environments, average levelized costs of electricity (LCOE) have been calculated as high as 38 €ct/kW h [23], in certain scenarios even exceeding 1 $/kW h [24] due to the dependence on diesel generators. In established grids of developed nations, LCOEs are however much lower. Here, the costs per cycle have to be considerably cheaper to enable a broad diffusion. Determining the most cost effective technology for an application highly depends on the expected required amount of cycles. In low frequency applications, technologies supporting less cycles can be favorable, if they are considerably cheaper (e.g. lead-acid). By contrast, in applications with higher frequencies, technologies comparably expensive per kW h (e.g. lithium ion) but supporting the required amount of cycles can be effectively cheaper [18]. For community scale energy management Battke et al. [18] cite 100 €/MW h as the electricity price and calculates LCOE of 0.25 €/kW h for lead-acid, 0.27 €/kW h for lithium-ion, 0.17 €/kW h for sodium-sulfur, and 0.18 €/kW h for vanadium redox flow. For other applications (e.g. increase of self-consumption by end users), much higher costs are given. Thus, LCOEs still have to drop considerably so that an application in established grids becomes financially attractive. Next to economies of scale, inventions for more cost-effective manufacturing methods, a higher number of supported cycles, and/or higher capacities (with otherwise undegraded parameters) are particularly needed to achieve competitiveness with conventional grid-based systems. Only strongly researched and manufactured technologies can hence be expected to approach relevant performance regimes. For trustworthy scenario forecasts, it is thus essential to know where progress is currently happening.

2. Selection of relevant patents with the novel Cooperative Patent Classification (CPC)

2.1. Previous innovation research in energy

For novel technologies, not yet sold in substantial units, little to no data is available, as firms usually seek to hide their research and market entry activities from competitors. Forecasting which of several candidate technologies might reach attractiveness due to economies of scale is therefore difficult. Next to R&D investment data on a country level (as published by the International Energy Agency and used in [25], for example), the only metric – particularly for the private sector – is patent data [26].

To identify favorable technologies, innovation research in energy technologies has attracted increased interest [27,28] during the last years, resulting in valuable insight into concentrated solar power [29], organic photovoltaics [30], CO_2 capture [31], and fossil fuel technologies [32]. However, there is limited knowledge on innovation in energy storage. Recently, Lin et al. [7] presented an investigation for electric mobility. Compared to electric mobility,

Table 2
Investigated technologies and their corresponding CPC classes. % denotes the wildcard for literal and logical subgroups (e.g. 10/052% includes 10/0525).

Technology	CPC subclass	Group(s) & subgroup(s)
Lithium	H01M	10/052%
	Y02E	60/122
	Y02T	10/7011
Alkaline, NiMH, NiCd	H01M	10/28%, 10/24–10/32, 4/24%, 4/24–4/34, 10/345
	Y02E	60/124
High-temperature batteries (e.g. sodium-sulfur)	H01M	10/3909–10/3981
Lead-acid	H01M	2/28, 4/14–4/23, 4/68%, 4/73–4/84, 10/12%, 10/06–10/18, 10/342
	Y02E	60/126
	Y02T	10/7016
Regenerative fuel cells (e.g. redox flow batteries)	H01M	8/188
	Y02E	60/528

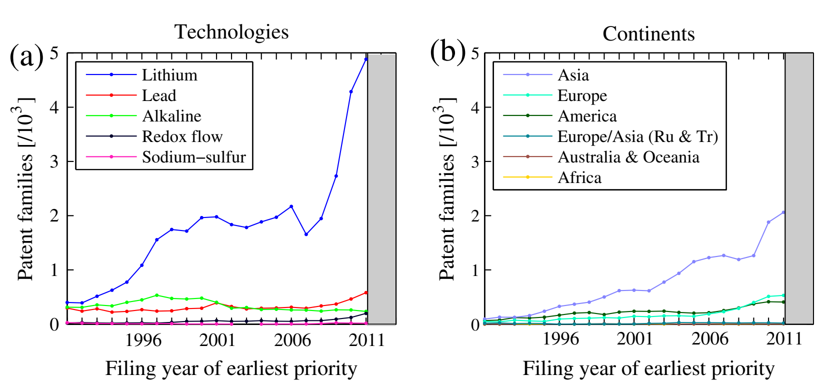

Fig. 2. (a) Total number of identified patent families of investigated technologies across filing years. Taking into account the issue date of PATSTAT (April 2014), data after 2011 is truncated due to the confidentiality period of applications (18 months, grey shaded) and limited proliferation of data from international authorities to the EPO. (b) Total number of identified patent families per continent of applicant country. Russia and Turkey are listed separately, as they are reaching over two continents.

Table 3
Most frequently cited patent families by technology groups as shown in Table 2. Citations were calculated patent-family to patent-family. A patent family is included if at least one family member is marked with at least one CPC subgroup listed in Table 2 for a technology. A family member of a major patent office (US, EP, CA, GB, DE, JP) and preferably published in English (thus not necessarily the priority) was chosen for a comprehensive overview in the table.

Forward citations	Applicant	Publication number	Publication date	Title of patent (application)
(1) Lithium batteries				
1337	Cabot	US7087341B2	08.08.2006	Metal-air battery components and methods for making same
662	NanoGram	US5952125A	14.09.1999	Batteries with electroactive nanoparticles
542	Angeion	US5235979B1	01.11.1994	Dual battery system for implantable defibrillator
489	William Marsh Rice University	CA2283502C	14.06.2005	Carbon fibers formed from singlewall carbon nanotubes
459	Bell Communications Research	US5296318A	22.03.1994	Rechargeable lithium intercalation battery with hybrid polymeric electrolyte
352	Medtronic	US5439760A	08.08.1995	High reliability electrochemical cell and electrode assembly therefore
311	Patterning Technologies	GB2330331B	10.04.2002	Method of forming a circuit element on a surface
242	PolyPlus Battery	US5523179A	04.06.1996	Rechargeable positive electrode
223	Black & Decker	EP1676427A4	02.04.2008	Methods of discharge control for a battery pack of a cordless power tool system, a cordless power tool system and battery pack adapted to provide over-discharge protection and discharge control
223	Toshiba	US6565763B1	20.05.2003	Method for manufacturing porous structure and method for forming pattern
(2) Alkaline batteries				
695	Nanomaterials Research	US5851507A	22.12.1998	Integrated thermal process for the continuous synthesis of nanoscale powders
662	NanoGram	US5952125A	14.09.1999	Batteries with electroactive nanoparticles
302	Alfred Mann Foundation	EP1424098B1	03.12.2008	Implantable device with improved battery recharging and powering configuration
165	Kyanon	JP2771406B2	02.07.1998	Secondary battery
127	Ovonic Battery	US5344728A	06.09.1994	Compositionally and structurally disordered multiphase nickel hydroxide positive electrode for alkaline rechargeable electrochemical cells
121	Energy Conversion Devices	US5096667A	17.03.1992	Catalytic hydrogen storage electrode materials for use in electrochemical cells and electrochemical cells incorporating the materials
106	Energy Conversion Devices	US6447942B1	10.09.2002	Alkaline fuel cell
106	Rayovac	US5567538A	22.10.1996	Metal-air cell having thin-walled anode and cathode cans
104	Ovonic Battery	US6255015B1	03.07.2001	Monoblock battery assembly
104	Chartec Laboratories	EP783200B1	09.07.2003	A method for charging a rechargeable battery
(3) Regenerative fuel cells – redox flow batteries				
116	Reveo	US6472093B2	29.10.2002	Metal-air fuel cell battery systems having a metal-fuel card storage cartridge, insertable within a fuel cartridge insertion port, containing a supply of substantially planar discrete metal-fuel cards, and fuel card transport mechanisms therein
106	Energy Conversion Devices	US6447942B1	10.09.2002	Alkaline fuel cell
89	Texas Instruments	US4021323A	03.05.1977	Solar energy conversion
88	Monsanto	US3691016A	12.09.1972	Process for the preparation of insoluble enzymes
85	Luz Electric Fuel Israel	WO9202964A1	20.02.1992	Rechargeable electrical power storage unit for use in electrical transport system
81	Aquanautics	EP176446B1	21.07.1993	System for the extraction and utilization of oxygen and other ligands from fluids
81	National Patent Development	US5804329A	08.09.1998	Electroconversion cell
77	T and G	EP370149B1	26.06.1996	Ionic semiconductor materials and applications thereof
70	The Penn State Research Foundation	US7491453B2	17.02.2009	Bio-electrochemically assisted microbial reactor that generates hydrogen gas and methods of generating hydrogen gas
66	Bloom Energy	EP1620906B1	08.01.2014	Co-production of hydrogen and electricity in a high temperature electrochemical system

Table 3 (*continued*)

Forward citations	Applicant	Publication number	Publication date	Title of patent (application)
(4) High-temperature batteries (e.g. sodium-sulfur)				
242	PolyPlus Battery	US5523179A	04.06.1996	Rechargeable positive electrode
116	Brown Boveri & Cie	DE3022449A1	07.01.1982	Elektrochemische Speicherzelle
91	Monsanto	US4175153A	20.11.1979	Inorganic anisotropic hollow fibers
65	Brown Boveri & Cie	GB1484437A	01.09.1977	Electrochemical storage cell or battery
55	Chloride Silent Power	US4383013A	10.05.1983	High temperature multicell electrochemical storage batteries
52	The Regents of the University of California	CA2053887C	11.12.2001	Cell for making secondary batteries
51	Powerplex Technologies	US4719401A	12.01.1988	Zener diode looping element for protecting a battery cell
50	Ford Motor	US3404035A	01.10.1968	Secondary battery employing molten alkali metal reactant
50	Robert Bosch	US4296148A	20.10.1981	Method to apply multiple layers, including an electrode layer, on a sintered or pre-sintered ion conductive solid electrolyte body
49	Chloride Silent Power	US4215466A	05.08.1980	Method of sealing ceramic electrolyte material in electrochemical cells
(5) Lead-acid batteries				
334	Telxon	US5773954A	30.06.1998	Battery charging station for shopping cart mounted portable data collection devices
317	ENSCI	US4713306A	15.12.1987	Battery element and battery incorporating doped tin oxide coated substrate
132	Massachusetts Institute of Technology	US7553584B2	30.06.2009	Reticulated and controlled porosity battery structures
129	Lucas Industries	GB2080550B	11.12.1985	Battery monitoring system
116	Seiko Instruments	EP582173B1	03.06.1998	Non-aqueous electrolyte secondary battery and its production method
106	Ztek	US5858568A	12.01.1999	Fuel cell power supply system
100	Globe-Union	US4876513A	24.10.1989	Dynamic state-of-charge indicator for a battery and method thereof
98	TRW	US3566717A	02.03.1971	Power train using multiple power sources
98	Commonwealth Edison	US4697134A	29.09.1987	Apparatus and method for measuring battery condition
98	Hyperion Catalysis International	AU765403B2	18.09.2003	Graphitic nanofibers in electrochemical capacitors

the relaxed energy density requirement in grid and residential applications also renders technologies such as redox flow cells and sodium-sulfur batteries interesting. As "a competition still exists between the [...] analyzed battery technologies and so far a leading technology has yet to emerge" [18], investigating the progress in these rivalling candidates is thus an important research gap, which this paper seeks to fill.

Previous research has identified patents of certain technologies either by searching for relevant keywords [7,30,31], by relying on technological classifications [32], or by employing an iterative combination of these two approaches [29]. A major risk of searching for keywords is the inclusion of irrelevant documents (e.g. describing novel technologies using the modules instead of describing improved modules) or omitting patents with a too narrow set of keywords.

2.2. The novel Cooperative Patent Classification

Selecting patents by technological classes – which all patent authorities assign to filed inventions – can circumvent this limitation, as the classification is assigned by skilled patent examiners, experts on patent literature in their technological field. The recent introduction of the Cooperative Patent Classification (CPC), between the USPTO and the European Patent Organization (EPO), allows the technologies (now approximately 250,000 distinct entries) to be resolved in a more refined manner than in the earlier International Patent Classification (IPC) [33]. Therefore, employing the CPC allows analysis of the parallel development with unprecedented discernment which so far has been rarely used. Also, major Asian patent offices – such as the State Intellectual Property Office (SIPO) of China and the Korean Intellectual Property Office (KPO) – have announced the introduction of the classification. It can thus be assumed that the CPC will soon become the internationally accepted standard for technological classification.

2.3. Energy storage classifications in the new CPC

As batteries are not a new technology as such, there have already been entries in the IPC, mainly in section H01M i.e. "processes or means, e.g. batteries, for the direct conversion of chemical into electrical energy". More detailed categories in the CPC now allow the allocation of patents to certain technologies, hereby enabling this trend study. In addition to the more detailed entries, the introduction of the class Y for "general tagging of new technological developments; general tagging of cross-sectional technologies spanning over several sections of the IPC" and, in particular, Y02E encompassing technologies for the "reduction of greenhouse gases [GHG] emission, related to energy generation, transmission or distribution" enable close monitoring and support of innovation in these areas. Furthermore, subclass Y02T, i.e. "climate change mitigation technologies related to transportation", has relevant entries.

We first searched for applicable CPC sections using keywords. This led us to the conclusion that relevant groups can be found in sections H and Y. Here, we manually screened all entries and assigned them (if at all) to the investigated technologies. Groups

Table 4
Top 10 patent-applicants within technology fields as divided in Table 2. A patent family is included in the underlying calculation if at least one family member is marked with at least one CPC subgroup listed in Table 2 for a technology. Applicants are ranked by h-index (i.e. where h is the number of patent families with more than h citations for an applicant). Source of descriptive data (if not otherwise stated) is the ThomsonONE database.

Company	h-Index	Country	Description of company
(1) Lithium batteries			
Fuji	39	JP	Manufacturer of industrial equipment with a division for power generation and social infrastructure
Matsushita	36	JP	Former manufacturing company, now Panasonic
Sony	33	JP	Operation of imaging products, games, mobile products and communication, amongst others
Mitsubishi	30	JP	Engaged in several business segments, amongst others electronics applications and chemicals
Sanyo	29	JP	Energy segment provides solar cells, cells for hybrid automobiles, lithium-ion batteries, amongst others
Toshiba	28	JP	Manufacturer digital product, electronic device, social infrastructure and home appliance segments
Samsung SDI	27	KR	Engaged in the manufacture and distribution of secondary cells and plasma display panels
Valence Technology	27	US	Develops, manufactures and sells energy storage systems utilizing its phosphate-based lithium-ion technology
Canon	27	JP	Manufacturing company with office, imaging and industrial equipment segments
NEC	26	JP	Diversified company, segments for IT solutions, carrier network, social infrastructure, personal solutions
(2) Alkaline batteries			
Matsushita	26	JP	Former manufacturing company, now Panasonic
Sanyo	20	JP	Energy segment provides solar cells, cells for hybrid automobiles, lithium-ion batteries, among others
Toshiba	19	JP	Manufacturer with segments digital product, electronic device, social infrastructure and home appliances
Canon	16	JP	Manufacturing company with the segments office, imaging and industrial equipment
Ovonic Battery	16	US	Manufacturer of rechargeable batteries, now subsidiary of BASF [38]
Toyota	15	JP	Mainly engaged in the automobile business and financial business
Yardney	15	US	Supplier of high energy density batteries for air, land, sea and space, subsidiary of ENER-TEK [39]
Energy Conversion Devices	15	US	Engaged in building-integrated and rooftop photovoltaics (PV)
Kawasaki	15	JP	Kawasaki Kasei chemical engaged in producing and selling organic acid products, amongst others
Panasonic	13	JP	Electronics manufacturer with segments for, amongst others, eco-solutions and automotive systems
(3) Regenerative fuel cells – redox flow batteries			
Kansai Electric Power	13	JP	Electric power supplier
Sumitomo	13	JP	Trading company with metal, transportation, construction, resources and chemical segments, amongst others
Kashima Kita Electric Power	9	JP	Developer of vanadium redox flow battery energy storage system; affiliate of mitsubishi group [40]
Unisearch	9	AU	Commercialization organization through which early inventors at the University of New South Wales filed for patents [41]
United States	8	US	NASA patents
Tokuda Nobuyuki	8	JP	Inventor
Deeya Energy	8	US	Redox flow battery developer, changed its name to Imergy Power Systems in December 2013 [42]
Hughes Aircraft	8	US	Former major American aerospace and defense contractor; some parts now owned by Raytheon [43]
Acal Energy	7	GB	Developer of low cost Proton Exchange Membrane (PEM) systems used to power fuel cells [44]
General Electric	7	US	Diversified technology and financial services company, amongst others power generation
(4) High-temperature batteries (e.g. sodium-sulfur)			
Ford Motor	16	US	Producer of automobiles
BBC Brown Boveri & Cie	14	CH	Group of electrical engineering companies; merged with ASEA to ABB in 1988 [45]
Chloride Group	12	UK	Supplier of power solutions, including the manufacture and sale of power supply systems, power conditioners
General Electric	11	US	Diversified technology and financial services company, amongst others power generation
Dow Chemical	9	US	Connects chemistry and innovation with the principles of sustainability
Asea Brown Boveri	9	CH	Engaged in the electrical engineering industry
Electric Power Res Inst	9	US	Research on issues related to the electric power industry in USA [46]
British Railways Board	8	GB	Responsible for most railway services in Great Britain; transferred to private sector in 1997 [47]
Comp Général Electricité	8	FR	Former electric and telecommunication company, now part of Alcatel-Lucent [48]
NGK Insulators	7	JP	Engaged in the provision of ceramic products, manufacturer of insulators and sodium-sulfur batteries
(5) Lead-acid batteries			
Globe Union	18	US	Former producer of automotive batteries, acquired by Johnson Controls in 1978 [49]
Matsushita	14	JP	Former manufacturing company, now Panasonic
General Motors	13	US	Designs, builds and sells cars, trucks and automobiles parts globally
Gates Energy Products	12	US	Developed e.g. sealed lead-acid cells in the 70s [50]
GNB	12	US	Now division of Exide Technologies [51]
Gould	11	US	Ancestor of GNB [51]
GS Yuasa	11	JP	Engaged in the manufacture and sale of batteries and power supply devices
Japan Storage Battery	10	JP	Battery manufacturer, merged with GS Yuasa to form Yuasa in 2004 [52]
VARTA	10	DE	Manufactures storage batteries for high-tech applications
Chloride Group	10	UK	Supplier of power solutions, including the manufacture and sale of power supply systems, power conditioners

describing battery technologies without reference to certain technologies were left out, as they were not useful to our investigation of the relative performance of the energy storage technologies. Table 2 shows the entries used in the investigation.

3. Development of patent intensity in the investigated technologies

One patent family is the set of all patent documents, linked by priority documents, and therefore most closely resembles individual inventions [32]. We consequently utilized this measure to compare the growth in the investigated technologies based on the latest available edition (April 2014) of PATSTAT. PATSTAT is a worldwide statistical database, which is issued bi-annually by the EPO (in the earlier issues jointly with the Organization for Economic Co-operation and Development (OECD)), to gather important data from major patent authorities around the globe. Fig. 2(a) shows the number of identified INPADOC families over the years of filing for the technologies as grouped in Table 2. Starting from a rather similar level in 1991, patent families relating to lithium have grown rapidly until now. The main growth can be attributed to mobile electronics and electric mobility. In the last few years, a slight increase can also be seen in lead and sodium-sulfur, although not to the same extent as lithium. Between 2009 and 2011, patent families in regenerative fuel cell and redox flow battery technologies doubled. Declining counts can be seen solely in alkaline batteries.

In the past, patent forward citations have been used to identify important patents, as it has been shown that valuable inventions are likely to exhibit an increased number of forward citations [34]. We thus calculated forward citations (i.e. how many times family members have been cited by newer patent families) for all identified patent families. Patents belonging to the 10 highest cited families are shown in Table 3.

To further gain insight into which organizations or individuals are driving innovation, we chose to reveal the most important patent filers within the technologies separately. Solely counting patents is however susceptible to distortions, if certain actors file large numbers of low-quality patents [35]. To circumvent limitations of this approach, it is necessary to add a qualitative perspective. We chose to combine quantitative and qualitative measures by using the h-index known from bibliometrics for patents [36]. The results of the identified leading applicants in every respective technological field are shown in Table 4.

3.1. Lithium batteries

Analyzing the applicants with top h-indices in lithium batteries, it is obvious that Asian firms have a dominating position. The predominant companies are big Japanese electronic conglomerates such as Toshiba, Panasonic or Sony, as well as the Korean firm, Samsung. With respect to highly cited patents, a good ratio related to lithium consists of inventions disclosing novel methods for various battery parts, i.e. improved electrolytes, improved electrodes and novel (mostly nanotechnological) fabrication procedures.

3.2. Alkaline batteries

In the area of alkaline batteries, Japanese companies, together with some US firms, dominate the list. The company with the highest h-index of the US firms, Ovonic Battery, was acquired by the German firm BASF when its parent company Energy Conversion Devices, went bankrupt in 2012.

The highly cited patent family "batteries with electroactive nanoparticles" appearing in the table for lithium batteries has been marked also as relevant for alkaline secondary cells. Even slightly more forward citations received the patent family including the family member "Integrated thermal process for the continuous synthesis of nanoscale powders". Rather related to the application of rechargeable batteries is the patent family encompassing "implantable device with improved battery recharging and powering configuration", showing that innovation in energy storage is also driven by medical technologies. The other cell patents are mostly related to inventions for improved electrodes.

3.3. Regenerative fuel cells – redox flow batteries

Regarding regenerative fuel cells, an almost even mixture between Japanese and American companies appears in the list. Sumitomo, a manufacturer of large redox flow batteries, holds a leading position. In general, much lower h-indices can be seen. Unlike the lithium technologies, where big industrial conglomerates dominate the list, also start-ups and even individual inventors are in the top ranks.

A member of the most cited patent family describes a metal-air fuel cell battery. The other frequently cited patent families describe different parts of regenerative batteries, from special cell types to cathodes and anodes to membranes.

3.4. Sodium-sulfur cells

Analyzing the leading institutions in high-temperature cells, the strong position of Ford becomes apparent. This could be explained by the fact that they pioneered the development in the 1960s [37]. Also the other leading companies in the list filed their applications a long time ago. BBC, ranked second, was acquired in 1998 and the third-ranked Chloride Group was most active two decades ago: that these companies still lead in h-index analysis suggests that the technological progress achieved back then has not yet been significantly overhauled by current inventions. The highest cited patent is a lithium-sulfur patent, highly cited due to the dynamics in lithium. The majority of other patents are comparably old and relate to inventions about the electrolyte and other material improvements (e.g. the use of expanded graphite as well as the production of β-alumina).

3.5. Lead-acid batteries

As mentioned before, the most common application of lead-acid batteries is as a starter battery in vehicles. This also explains the large number of automotive supplier companies in the list of top innovators in lead-acid batteries. Again, the lion's share of the patents can be assigned to Japanese and American companies. From analyzing the top cited patents relating to lead-acid batteries, it is apparent that some of the patents describe the improved application of batteries and not the batteries themselves. This can however also be seen as a sign of the technology's maturity. Nevertheless, there are also a number of patents documenting improved modules.

4. Conclusion & discussion

The analysis of leading applicants and their countries of origin has important implications for public policy. A clear dominance of certain world regions can be seen by the tables in Sections 3.1-3.5. This needs to be considered by local policy makers who are trying to incentivize further development of storage technologies. Market-pull subsidies might benefit the now well-positioned firms, whereas technology-push initiatives could also enable others. These results have to be considered in addition to ongoing considerations with respect to demand-pull vs. technology-push subsidies [53]. The absence of European firms in the ranks for high h-indices in lithium technologies in any case calls for in-depth investigations regarding research policy.

In analyzing the most frequently cited patents, it becomes apparent that these are comparably new in lithium, supporting the reasoning that there is ongoing innovation dynamics in lithium technologies. This is in contrast to, for example, sodium-sulfur where most of the highly cited patents stem from the 80s or even earlier. Also in absolute patent numbers, (compare Fig. 2) patenting in lithium technologies shows a surprisingly strong rate compared to other types of batteries. It appears that the scepticism with respect to safety – apparent in the application dip in 2007 after the product recall campaigns of 2006 [54] – has been overcome. In the future, continued growth could lead to a self-multiplying effect: the techno-economic parameters of lithium related technologies could be more attractive compared to others, leading to even more R&D in this field, thus further improving the performance of these batteries. We believe that our findings of growing patent applications in batteries – in particular lithium-based technologies – are encouraging, as they are indicative of continued module improvements. In addition, the surge of patents indicates increased capabilities in supplying ameliorated cells because of which the much-needed price reductions can be expected in the future.

We see our letter as a potential starting point for more rigorous investigations into the innovation of sub-branches in auspicious technologies, such as lithium-sulfur [55], for example. Further research could, for example, investigate which technology clusters are still mainly patented by university applicants and which by firms, hereby allowing further conclusions on which technologies might reach market readiness in the near future.

Moreover, it would be worthwhile to investigate the fundamentally different storage technology candidates (such as compressed air and superconducting magnetic energy storage) for their maturity in comparison to electrochemical cells using the presented methodology and results.

Acknowledgements

The authors would like to thank the Bavarian Ministry of Economic Affairs and Media, Energy and Technology for their financial support via the EEBatt project. Maximilian Schreieck is acknowledged for his assistance in illustration and data preparation.

References

[1] Nicolosi M. Wind power integration and power system flexibility–an empirical analysis of extreme events in Germany under the new negative price regime. Energy Policy 2010;38(11):7257–68.
[2] Armand M, Tarascon J. Building better batteries. Nature 2008;451(7179):652–7.
[3] Baker J. New technology and possible advances in energy storage. Energy Policy 2008;36(12):4368–73.
[4] Dunn B, Kamath H, Tarascon J. Electrical energy storage for the grid: a battery of choices. Science 2011;334(6058):928–35.
[5] Hall PJ, Bain EJ. Energy-storage technologies and electricity generation. Energy Policy 2008;36(12):4352–5.
[6] Lindley D. Smart grids: the energy storage problem. Nature 2010;463(7277):18–20.
[7] Lin YP, Chang YC, Sung TL, Lin TC. The Evolution of Electric Vehicle Lithium Battery Technology: Towards SSI Perspective. In: 35th DRUID celebration conference 2013, Barcelona, Spain, June 17–19; 2013.
[8] Hannen P. Rekord: Über 60 Prozent Strom aus Sonne und Wind. PV Magazine; 2013.
[9] Herbrich V. Rekord: Am Muttertag kam 73 Prozent des Stroms aus erneuerbaren Energien. Huffington Post 2014, 14 May 2014; <http://www.huffingtonpost.de/2014/05/14/rekord-erneuerbare-energien_n_5321800.html>. [May 27, 2014].
[10] Drouineau M, Maïzi N, Mazauric V. Impacts of intermittent sources on the quality of power supply: the key role of reliability indicators. Appl Energy 2014;116:333–43.
[11] US Department of Energy. Global Energy Storage Database: Project 69. [February 28, 2014]; <http://www.energystorageexchange.org/projects/69>.
[12] 50Hertz, Amprion, TenneT, TransnetBW. EEG-Anlagenstammdaten zum Stichtag 31.12.2012. [May 20, 2014]; <https://www.netztransparenz.de/de/Anlagenstammdaten.htm>.
[13] Mayer J, Burger B. Electricity Spot-Prices and Production Data in Germany 2013. [May 20, 2014]; <http://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/boersenstrompreise-und-stromproduktion-2013.pdf>.
[14] ENTSO-E. Statistical Database. [May 20, 2014]; <https://www.entsoe.eu/data/data-portal/>.
[15] European Energy Exchange. Transparency in Energy Markets – Tatsächliche Produktion. [May 20, 2014].
[16] European Power Exchange. APX, BELPEX and EPEX spot statement about negative baseload prices on 16 June 2013. [May 20, 2014]; <http://www.epexspot.com/de/presse/news-archive/details/news/23538>.
[17] Chang Y, Mao X, Zhao Y, Feng S, Chen H, Finlow D. Lead-acid battery use in the development of renewable energy systems in China. J Power Sources 2009;191(1):176–83.
[18] Battke B, Schmidt TS, Grosspietsch D, Hoffmann VH. A review and probabilistic model of lifecycle costs of stationary batteries in multiple applications. Renewable Sustainable Energy Rev 2013;25:240–50.
[19] Chatzivasileiadi A, Ampatzi E, Knight I. Characteristics of electrical energy storage technologies and their applications in buildings. Renewable Sustainable Energy Rev 2013;25:814–30.
[20] van Noorden R. The rechargeable revolution: a better battery. Nature 2014;507(7490):26–8.
[21] NGK Insulators, Ltd. Q&A Concerning the NAS Battery Fire; 2012.
[22] Pieper C, Rubel H. Revisiting energy storage: there is a business case. BCG perspectives. Energy & Environment Publications; 2011.
[23] Blechinger P, Seguin R, Cader C, Bertheau P, Breyer C. Assessment of the global potential for renewable energy storage systems on Small Islands. Energy Procedia 2014;46:294–300.
[24] Tollefson J. Energy: islands of light. Nature 2014;507(7491):154–6.
[25] Gallagher KS, Anadon LD, Kempener R, Wilson C. Trends in investments in global energy research, development, and demonstration. WIREs Clim Change 2011;2(3):373–96.
[26] Daim TU, Rueda G, Martin H, Gerdsri P. Forecasting emerging technologies: use of bibliometrics and patent analysis. Technol Forecasting Social Change 2006;73(8):981–1012.
[27] Bettencourt, Luís MA, Trancik JE, Kaur J, Hernandez Montoya, Alejandro Raul. Determinants of the pace of global innovation in energy technologies. PLoS ONE 2013;8(10):e67864.
[28] Lee K, Lee S. Patterns of technological innovation and evolution in the energy sector: a patent-based approach. Energy Policy 2013;59:415–32.
[29] Braun FG, Hooper E, Wand R, Zloczysti P. Holding a candle to innovation in concentrating solar power technologies: a study drawing on patent data. Energy Policy 2011;39(5):2441–56.
[30] Lizin S, Leroy J, Delvenne C, Dijk M, de Schepper E, van Passel S. A patent landscape analysis for organic photovoltaic solar cells: identifying the technology's development phase. Renewable Energy 2013;57:5–11.
[31] Li B, Duan Y, Luebke D, Morreale B. Advances in CO_2 capture technology: a patent review. Appl Energy 2013;102:1439–47.
[32] Lanzi E, Verdolini E, Haščič I. Efficiency-improving fossil fuel technologies for electricity generation: data selection and trends. Energy Policy 2011;39(11):7000–14.
[33] Ross P, Fucito P, Coggins W. USPTO and EPO Announce Launch of Cooperative Patent Classification System: USPTO Press Release. Washington; 2013.
[34] Harhoff D, Narin F, Scherer FM, Vopel K. Citation frequency and the value of patented inventions. Rev Econom Stat 1999;81(3):511–5.
[35] Wu C, Hu M, Mathews JA. Technology: internal factors drive Chinese patent surge. Nature 2014;509(7501):427.
[36] Guan JC, Gao X. Exploring the h-index at patent level. J Am Soc Inf Sci 2009;60(1):35–40.
[37] Davidson P. New battery packs powerful punch. USA TODAY 2007, 4 July 2007; <http://usatoday30.usatoday.com/money/industries/energy/2007-07-04-sodium-battery_N.htm>. [May 23, 2014].
[38] BASF. Nickel Metal-Hydride. [May 29, 2014]; <http://www.catalysts.basf.com/p02/USWeb-Internet/catalysts/en/content/microsites/catalysts/prods-inds/batt-mats/NiMH>.
[39] Yardney Technical Products. General Company and Corporate Information. [29 May, 2014]; <http://www.yardney.com/>.
[40] Mitsubishi Chemical Holdings Group. Corporate Data. [29 May, 2014]; <http://www.mitsubishichem-hd.co.jp/english/ir/pdf/11_15.pdf>.
[41] Kear G, Shah AA, Walsh FC. Development of the all-vanadium redox flow battery for energy storage: a review of technological, financial and policy aspects. Int J Energy Res 2012;36(11):1105–20.
[42] CrunchBase. Imergy Power Systems, Inc. [29 May, 2014]; <http://www.crunchbase.com/organization/imergy-power-systems-inc>.
[43] Federation of American Scientists. Raytheon Company and Hughes Electronics' Defense Business to Merge. [May 29, 2014]; <http://www.fas.org/man/company/docs/970116-raytheon.html>.
[44] ACAL Energy Ltd. ACAL Energy Ltd - Next generation affordable fuel cells. [May 29, 2014]; <http://www.acalenergy.co.uk/>.
[45] ABB. History. [May 29, 2014]; <http://new.abb.com/about/abb-in-brief/history>.
[46] EPRI. EPRI – Electric Power Research Institute. [May 29, 2014]; <http://www.epri.com/>.
[47] Government of the United Kingdom – The National Archives. Records created or inherited by the British Transport Commission, the British Railways Board, and related bodies. [May 29, 2014]; <http://discovery.nationalarchives.gov.uk/SearchUI/details?Uri=C12>.
[48] Alcatel-Lucent. History. [May 29, 2014]; <http://www.alcatel-lucent.com/about/history>.
[49] Johnson Controls Inc. 1960–1985 – Expanding Into New Opportunities. [May 29, 2014]; <http://www.johnsoncontrols.com/content/us/en/about/our_history/1960-1985.html>.
[50] Gates Energy Products, Inc., Rechargeable batteries applications handbook. Boston: Butterworth-Heinemann; 1998.
[51] Wohlleben K. The History of Exide Technologies. [May 29, 2014]; <http://www.exide.com/Media/files/The%20History%20of%20Exide%20Technologies.pdf>.
[52] GS Yuasa. History. [May 29, 2014]; <https://www.gs-yuasa.com/us/corporate/pdf/a4_history(e).pdf>.
[53] Nemet GF. Demand-pull, technology-push, and government-led incentives for non-incremental technical change. Res Policy 2009;38(5):700–9.
[54] Jacoby M. Burning Batteries: hazardous failures of lithium-ion batteries are uncommon, yet researchers strive to minimize dangers. Chem Eng News 2007;85:26–8.
[55] van Noorden R. Sulphur back in vogue for batteries. Nature 2013;498(7455):416–7.