Start-ups as technology life cycle indicator for the early stage of application – An analysis of the battery value chain

Abstract: Insights from battery research and development (R&D) need to be transferred into industrial application to create innovations and thus foster e.g. electro mobility. In terms of battery technology transfer, the early phase of application is particularly challenging due to the close intertwining between R&D and application. Therefore, the present study introduces start-ups as an additional indicator to capture the transition from science to industry within the technology life cycle. The findings show that despite highly dynamic R&D activities, technology transfer is only taking place on a very limited level. Surprisingly, start-ups focus on incremental improvements of existing technologies instead of introducing radical breakthrough-technologies. An analysis of the battery value chain reveals that opportunities for start-ups are rather located downstream in the value chain when integrating cells to battery systems and developing applications relying on innovative battery technologies. The findings contribute to the area of technology life cycle analysis explicitly using start-up companies as additional indicator for the critical transfer step from R&D to application. In a similar vein, technology forecasting literature, which is to date mainly focused on R&D, is expanded by a more application-centred perspective that allows identifying transfer opportunities along the technology value chain.

Keywords: batteries; patent analysis; publication analysis; start-up; technology life cycle; technology transfer

1 Introduction

Energy storage devices and particularly batteries are decisive technologies to tackle climate change. Stationary storage opportunities support the extensive use of renewable energies while batteries in electric vehicles (EV) secure individual mobility independent from fossil fuels (Lund et al., 2015, Longo et al., 2014, Kley, Lerch et al. 2011, Dunn, Kamath et al. 2011). In order to tackle the grand global challenges and reach ecological and societal goals, improved batteries are needed to successfully enter new markets or for mass-market penetration of EV (Goodenough, Kim 2011). For this reason, intensive research and development (R&D) activities are going on, resulting in new materials or innovative cell chemistries (Liu 2010, Scrosati, Garche 2010). But these R&D insights need to be transferred into industrial application to create innovations and thus foster electro mobility. To date, a lot of attention in literature has been paid to battery R&D, e.g. scientific publication and patent analyses to identify upcoming technologies (Wagner, Preschitschek et al. 2013, Golembiewski, vom Stein et al. 2015). However, the transferability and the actual transfer of R&D achievements into practice has only been tackled by a very limited number of studies (Chevrier, Liu et al. 2014, Krätzig, Sick 2017).

To enable a more comprehensive understanding of the transfer process, the current paper proposes a life cycle perspective to capture the whole battery innovation process from basic to applied research and development and particularly reaching until commercialization and industrial application. Current indicators to analyse the technology life cycle comprise scientific publications for basic research, patents for applied research and development as well as new product launches for application (Watts, Porter 1997, Bornkessel, Bröring et al. 2016). The clear tendency in the structure of these indicators towards R&D activities is particularly helpful for technology forecasting purposes, where early information on new technological developments is crucial. However, new technologies need to be successfully launched into the market to reach their potential and create economic and societal impact, which is especially relevant for technologies facilitating sustainability and energy safety. Since new product launches as an indicator for application might not always be observable yet, an additional indicator reflecting the early phase of application and thus the transition from R&D to application is highly desirable. One way to transfer newly developed, and particularly risky technologies into practice are start-up companies (Swamidass 2013). Start-ups with their organizational flexibility in comparison with large corporations and at the same time their proximity to research-intensive environments as e.g. university spin-offs are predestined to represent the early phase of application within a technology life cycle (Clarysse and Moray, 2004; Huynh et al., 2017).

Historic as well as recent developments in the battery market underline the need for a thorough analysis of the technology life cycle. It is particularly interesting to note that during the last century, only three batteries, namely, the manganese oxide (MnO_2) primary battery and the secondary batteries of lead-acid or nickel have been in use in mass markets before lithium-ion technology has been introduced in 1991 by Sony. Even more remarkable, no battery technology when successfully introduced into a commercial mass market has been replaced in its applications for many decades. For example, lead-acid batteries, developed more than 100 years ago, are solidly established in their applications and have still one of the biggest market shares globally given by the starter battery application for cars and back-up power in stationary industrial applications. An explanation for this phenomenon might be that each battery technology seems to be particularly designed and adapted to the application and vice versa. In a way, a battery is never an autonomous piece of technology, but rather presents a system solution. Hence, its performance is a result of a negotiation with its application and the system it is built in. Thus, one can observe a high resource complementarity, reflected in a systems approach, where R&D and application are deeply interwoven. For example, despite having more powerful and reliable battery technologies at hand, switching the starter battery technology from lead-acid to lithium-ion did not take place yet, because of costs in this massive market, but also because of the 12 V requirement for which all automotive electronics are built for. Also, the voltage of the mobile phone electronics is adjusted to the voltage of the cell and vice-versa. An exchange of the battery voltage would need significant adjustment of electronics components, which is challenging in times of mass production and high degrees of standardization. Furthermore, when introducing lithium ion batteries into the market, Sony did this with their own camcorders, which were in need of batteries with higher energy content in order to fulfil customer requirements.

Although battery R&D is closely intertwined with its respective applications, the focus of current research has been set on R&D, widely neglecting application and particularly the transfer from R&D to industrial application. But to fully grasp technological developments in the battery field, the whole technology life cycle needs to be taken into consideration. The study at hand aims to close this gap by scrutinizing the specifics of the battery technology life cycle and how the transfer from R&D to application and thus the early phase of industrial application can be analysed in more detail. For this purpose, technology life cycle indicators are used, i.e. scientific publications, patents and new product launches as indicators for basic research, applied research and development as well as application (Watts, Porter 1997). Considering the transfer from R&D to application, the study strives to extend the approach developed by Bornkessel, Bröring et al. (2016) and introduce start-up companies as an additional indicator to capture the early phase of application. The subsequent analysis of opportunities and barriers for start-up companies along the battery value chain provides detailed insights on where and how start-ups can be used best to foster technology transfer.

The contributions of the present study to the technology forecasting literature are twofold. First, the study adds to technology life cycle analysis explicitly using start-up companies as additional indicator for the transfer step from R&D to application. Thereby, a contribution is made to the development of technology life cycle indicators, which, yet, have focused on publications and patents for R&D as well as new product launches for application (Bornkessel, Bröring et al. 2016). Start-ups as additional application-oriented indicator allow detailed insights into the early phase of application, where product launches might not yet be observable. This is not only relevant for batteries, but holds true for all sustainable technology-driven environments, where technology transfer is often hindered by established, more cost efficient technologies and is largely dependent on policy measures such as subsidies or quotas. This is due to path dependencies causing a sailing ship effect, whereby the emergence of a new technology temporarily leads to an increase in investment and innovation effort in the established technology (Sick et al., 2016). Insights into opportunities and barriers for start-ups could guide the way for more effective policy measures and thus technology transfer for sustainable technologies. Second, and based on this new approach, technology forecasting literature, which is to date mainly focused on R&D, is expanded by a more application-centred perspective that allows identifying transfer opportunities along the technology value chain. This is particularly valuable for technological fields, where R&D and application are closely intertwined. In these cases, early information on possible and upcoming application fields is critical to successfully bring new technologies into the market.

The remainder of this article is organized as follows. Section 2 presents theoretical background on technology life cycle analysis. Subsequently, section 3 elaborates on the databases and search strings used to obtain the respective data in section three, while section four encompasses analyses and discussion. The work is concluded in section five with a short summary of the main results as well as implications and avenues for further research.

2 Technology life cycle indicators

Referring to the concept of product life cycles (Brockhoff, 1967; Day, 1981; Midgley, 1981; Easingwood, 1988), technology life cycles depict the development over time for the different stages of technological change (Ernst, 1997). This can be traced to the relationship between technological performance and cumulative R&D expenditure, which follow an S-shaped course (Merino, 1990). To describe the technology life cycle, the analysis draws on the indicators developed by Watts and Porter (1997) and adapted by Bornkessel, Bröring et al. (2016) (Figure 1). Thereby, the focus is on the R&D profile of the technology life cycle from basic and applied research to development and application (Watts, Porter 1997). The initial phase of the technology life cycle, basic research, is represented by scientific publications drawn from general databases such as Scopus, Science Citation Index or discipline-specific databases such as Chemical Abstracts Service. The next phase, applied research and development, can be captured using patents from either databases of the respective national patenting authorities or comprehensive databases such as PatBase or Thomson Innovation (Bornkessel et al., 2014, Gao et al., 2013, Haupt et al, 2007). The third and last phase, application, is indicated by new product launches communicated in general (business) media such as newspaper articles, reports or press releases (Bornkessel et al., 2016).

As many sustainable technologies such as new battery technologies are still in their infancy, new product launches might not always be observable yet (Kushnir and Sanden, 2011). To fully cover the important and often neglected step of application and to put particular emphasis on the transfer from R&D to application, the present study strives to further elaborate the approach developed by Bornkessel, Bröring et al. (2016) and proposes to use start-up companies in the respective field as an additional proxy for the early application stage. Due to the aforementioned need for integration and close development of batteries in alignment with the entire application of novel battery technologies, start-ups seem to play a very important role. A major driver can be seen in the organizational rigidity (Leonard-Barton, 1992) of established firms, thus, needed resource combination and combinative capabilities (Kogut, Zander, 1992) are more likely to be deployed in a start-up organisation. Their agile and flexible structure allows start-ups to pick up new technological trends and bring new technologies and thus products to market maturity more quickly than established players. In addition, start-ups often arise in a research-intensive environment, e.g. as spin-offs from universities or other research networks (Clarysse and Moray, 2004; Huynh et al., 2017). Their proximity to R&D, but at the same time their inherent application and market orientation predestines start-ups as a bridge builder between R&D and application (Zhang, 2009). Therefore, start-ups represent a reliable proxy to assess the early phase of application in the technology life cycle as a transition between R&D and application. Thus, the new indicator fills the gap between patent and reported product launches (see Figure 1).

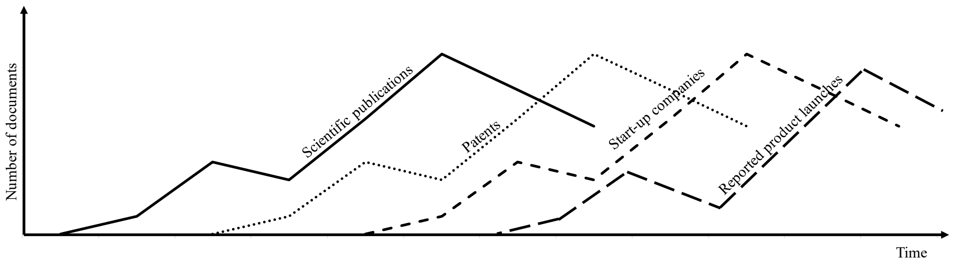

Figure 1 Technology life cycle indicators.

Source: Based on Bornkessel et al. (2016).

The timely development of the abovementioned indicators is supposed to follow a typical s-shaped course (Bornkessel, Bröring et al. 2016, Ernst 1997, Järvenpää, Mäkinen et al. 2011). When comparing the timely development of the indicators, a time lag between them can be assumed. The size of the time lag indicates “the time between successively higher levels of performance in the industry’s product technology evolution”, referred to as technology industry clockspeed (Dedehayir, Mäkinen 2011). Technology industry clockspeed can substantially differ between industries due to varying speed of implementing technological change (Suarez, Lanzolla 2005). This might be a decisive point for batteries as an interdisciplinary field since the development of batteries has lagged behind e.g. semiconductor and display industry by decades. Whereas according to Moore´s law the number of transistors per integrated circuit chip doubled every 12 to 24 months, the time spans of the improvement of energy densities in batteries has to be counted in decades rather than years (Lundström 2003). Improving the energy content of a lithium-ion battery from 900 mAh (milli Ampère hours) to above 3500 mAh for a standard 18650 battery format took 25 years of intense development work, moreover hitting now physical and chemical limits. Another doubling of the energy density is currently not foreseen, neither with existing technologies nor novel disruptive technologies. Although several technologies including lithium-air would have the potential for a major step, their maturity is by far not advanced enough for a successful market introduction (Thackeray et al. 2012). In this respect, the consideration of technology industry clockspeed seems of major importance when analysing the battery technology life cycle.

3 Data and methods

To identify the specifics of the battery technology life cycle and how the transfer from R&D to application and thus the early phase of industrial application can be analysed in more detail, a technology life cycle analysis is conducted in the field of lithium battery technologies. Considering the business and technological maturity of previously established batteries like lead acid or nickel-metal hydride, we focus on lithium battery technologies with the strongest technology and market development during the last almost three decades (Avicienne Energy, 2017). Although lithium batteries have already been commercially introduced by Sony in 1991, only very few players were active in this market in the following decade. During this time, lithium batteries were used for a narrow range of special applications, e.g. by Sony for camcorders. The broader use of lithium batteries for consumer electronics and major automotive applications only gained momentum since the beginning of the new millennium, as did the publishing and patenting activities. Since then, further lithium based battery technologies have been developed and partially commercialized, e.g. lithium sulphur or lithium air (Manthiram, Fu et al. 2013, Girishkumar, McCloskey et al. 2010). Therefore, a starting point of the analyses in the year 2000 reflects best the contextual and industrial boundary conditions of this particular case. Because of the lag of 18 months in publishing patent applications, the analysis includes 2014 as the last full year available.

The technology life cycle analysis is conducted based on the abovementioned indicators (scientific publications, patents, start-up companies and reported product launches) to reflect the respective stages of the technology life cycle (see Table 1). Basic research activities are captured via scientific publication analysis. Elsevier's database SCOPUS is used with the search term TITLE-ABS-KEY (lithium AND batter*) to extract journal articles in the field of lithium batteries. To identify applied research and development activities, patent analysis is conducted in PatBase, a database provided by Minesoft with a global coverage of more than 110 million patents and related documents from over 100 issuing authorities. A combined search term of International Patent Classification and keywords is applied, namely H01M (PROCESSES OR MEANS, e.g. BATTERIES, FOR THE DIRECT CONVERSION OF CHEMICAL ENERGY INTO ELECTRICAL ENERGY) and "lithium" in title, abstract and claims. For the identification of start-up companies, Crunchbase as a global business information platform is used. Crunchbase provides very suitable information for analysing start-ups such as investors, acquired venture capital in different rounds of financing or own acquisitions. Start-ups founded between 2000 and 2014 are included, using "lithium" and "batter*" as search terms. Product launches are depicted using Nexis, a database containing general business information media such as newspaper articles, reports, and press releases (Bornkessel, Bröring et al. 2016). The search string is "lithium W/5 (within 5 words) batter*" in headline, lead paragraphs and indexing in All English language news. Additionally, non-business news and group duplicates are excluded. The search results are refined by the predefined category "new products". The resulting documents are carefully reviewed and double-checked regarding product launches.

Table 1 Life cycle indicators and data sources.

Life cycle stages	*Indicator*	*Database*
Basic research	Scientific publications	Scopus
Applied research and development	Patents	PatBase
Early application	Start-up companies	Crunchbase
Application and diffusion	New product launches	Nexis

Subsequently, start-up companies as well as new product launches are classified according to the steps of the battery value chain (Figure 2). Value creation in the battery industry comprises four steps: materials, cell (components), battery (system) and application. At the beginning of the value chain, cathode, anode, electrolyte, separator and other materials are synthesised based on the respective raw materials. Subsequently, the different components and cells are assembled in an integrated production. Next, the cells are packed to a battery (system) and finally integrated into the respective applications (Majeau-Bettez et al., 2011; Notter et al., 2010).

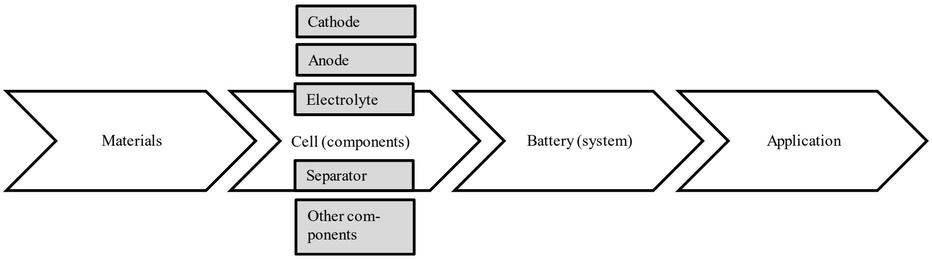

Figure 2 Battery value chain.

Source: Golembiewski et al. 2015.

Based on the four technology life cycle indicators, the different patterns of how a technology life cycle evolves are described and analysed. Additional data such as industry reports are used to triangulate the findings provided by technology life cycle analysis. Following the time gaps between basic research, applied research and development as well as application, conclusions are drawn concerning battery technology industry clockspeed. The classification of start-ups and new product launches to the respective value chain steps additionally allows identifying hurdles and starting points for battery technology transfer.

4 Findings and discussion

4.1 Battery technology life cycle

Increasing publication activity is observed in the field of lithium batteries with a total of 28,219 scientific articles published between 2000 and 2014 (Figure 3). The subject areas covered are predominantly chemistry, materials science, engineering, energy, physics and astronomy as well as chemical engineering, reflecting the interdisciplinary nature of battery research. In order to assess quality in addition to quantity, the most active countries considering the 300 most cited articles as Top 1% of the sample are the United States, China, South Korea, Japan, and Germany. Here, the Top 5 institutions are the Chinese Academy of Sciences, Stanford University, Nanyang Technological University, Massachusetts Institute of Technology as well as Argonne National Laboratory.

A similar pattern can be observed in terms of patenting activities based on 26,439 patent families with 45,765 individual patents on lithium batteries, which have been filed by 3,293 assignees. In contrast to scientific publications, the most active patent assignees are limited to South Korean and Japanese companies, namely LG Chem, Panasonic, Samsung, Sanyo, Sony, and Toyota and with more than 500 patents each. The only non-Asian based company among the Top25 assignees is German Robert Bosch GmbH. This is a reflection of the actual structure of the battery industry, where despite the plans for Tesla's Giga factory in the US, the main cell and battery manufacturers are exclusively based in Asia.

The strong increase in publications since 2006 and in patents since 2008 confirms that a large variety of different materials and cell chemistries as a foundation for high performance batteries is available. The development of scientific publications and patents follows the typified S-shape as suggested by Ernst (1997). But surprisingly, no time lag becomes apparent between basic research represented by scientific publications and applied research and development reflected by the total number patents per year. An explanation for this timely congruence can be seen in the abovementioned application orientation of battery research, i.e. that every battery technology is custom-tailored to the respective industrial application. The higher number of patents than scientific publications also hints towards a particular application focus of battery research. It also points out how much industrial R&D is conducted in this area and how large the potential economic impact of innovative battery technology is. Moreover, the fact that so many patent applications are filed indicates the unlimited number of materials and process combinations possible in lithium battery technology. On the other hand, the basic principles of different battery technologies are far from fully understood, so that many improvements in performance are a matter of trial and error rather than systematic application of knowledge. The poor understanding of the complex interplay of the components and the large variations of materials is very well reflected in the still growing number of scientific publications.

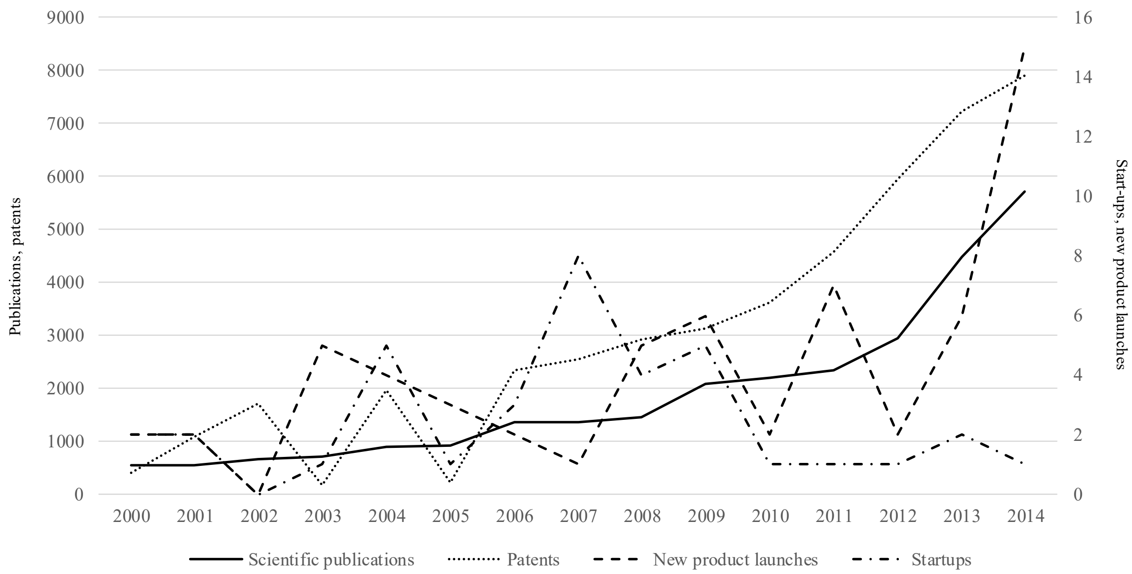

Figure 3 Technology life cycle patterns of lithium batteries.

Sources: Scopus, PatBase, Crunchbase, Nexis.

In terms of the early phase of application, 37 start-up companies are identified in the field of lithium batteries. Surprisingly, there are very few start-ups producing battery technologies beyond the established LIB. 32 out of 37 start-ups focus on further improving lithium ion technologies, e.g. via improved separators or active materials. In contrast, only five start-ups go beyond LIB and develop as well as manufacture super capacitors for lithium batteries, lithium batteries based on solid state electrolytes and metallic lithium, lithium sulphur or lithium polymer batteries. The first start-ups in this period of study appeared in 2002 with a peak of eight newly founded companies in 2008. In the following years, the number of start-ups constantly declined, so that between 2010 and 2014, only six new lithium battery companies were founded. Compared to the steeply increasing R&D activity in terms of scientific publications and patents since 2008, this seems even more contradictory. When assigning the start-ups to the battery value chain (Figure 4), it becomes obvious that most of the newly founded companies dedicate themselves to cell (components) and/or battery (system) development and manufacturing. Only four start-ups operate at the beginning of the battery value chain producing specific materials. Hence, there seems to be more dynamic in the downstream positions of the value chain. Although at the level of application, yet, no start-up exists.

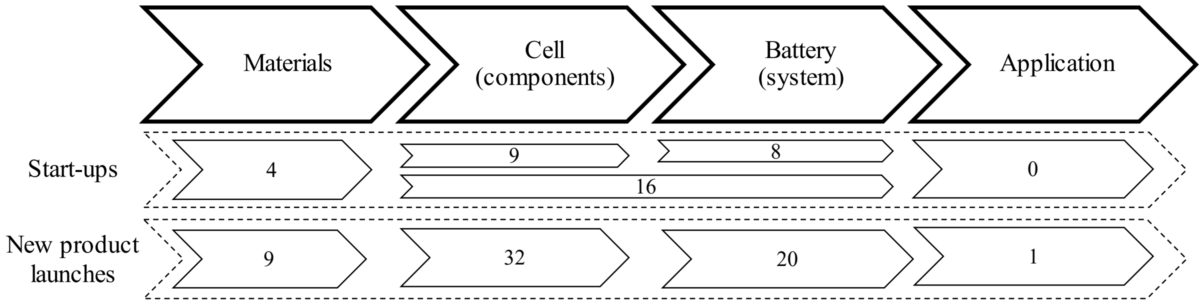

Figure 4 A value chain perspective on start-ups and new product launches for lithium batteries.

Sources: Crunchbase, Nexis.

Concerning new product launches, the search in Nexis identifies 1081 news documents, 931 after excluding duplicates. After manually scanning these documents, 62 new product launches can be identified between 2000 and 2014, indicating the later phase of application. Lagging behind scientific publications and patents, new product launches only gained serious momentum since 2012, with a peak of 15 new products in 2014. Corresponding to the findings concerning start-ups, the vast majority of new product launches relates to incremental improvements in LIB technologies such as modified separators or active materials. When aligning the new product launches to the steps of the battery value chain, it becomes obvious that more than half of the new products (32) are related to cells and cell components as centrepiece of the value chain (Figure 4). New products concerning materials (9) are less frequent. While battery (systems) account for about one third (20) of the new products, there is only one launch directly linked to a specific application. Although application opportunities are marginally mentioned in a number of documents concerning other value chain steps, the missing application focus may surprise as batteries need to be custom-tailored for different applications with vastly differing requirements concerning weight, volume, costs, and performance.

It can be concluded that, concerning different kinds of lithium batteries as most promising current and future technologies, basic research as well as applied research and development do not show the expected time lag due to the strong application orientation. They are rather taking place at the same time, in research institutions as well as on corporate level. In terms of application, start-ups surprisingly focus on incremental improvements of existing technologies instead of introducing radical breakthrough-technologies. This is also reflected in the new product launches, which mainly concentrate on the cell (components) and battery (system) level than on actual applications. Another striking finding is the vast difference in numbers between scientific publications and patents on the one hand and start-ups and new product launches on the other hand. While we observe 6000 scientific publications and 8000 patents in 2014, a maximum of 8 start-ups and 15 new product launches per year is reached during the whole period of analysis. The gap in the lithium battery technology life cycle thus becomes apparent between R&D and application more than between basic research, applied research and development and application as single steps of the technology life cycle.

In terms of industry clockspeed, the size of this gap points towards long life cycles that even tend to increase. This is due to path dependencies caused by the close link between the battery technology and the respective application (system solution), which slow down battery industry clockspeed substantially. Life cycles of battery technologies in general may comprise many decades. The success of battery development - which is characterised by a vast cost and time requirement – thus primarily depends on market sensing and collaboration abilities and a strong market pull (Schoemaker, Day 2009). Once a battery technology is developed in synergy with its application, it only disappears when the application seizes to exist. It will be very interesting to observe, if the e.g. the lead-acid battery will only disappear with the complete substitution of cars with internal combustion engines by battery EV or, if they will be replaced by another battery technology in this application. In another aspect, the situation becomes complex due to the fact that the once application-driven developed battery technology spreads to other applications – e.g. from camcorder to mobile phone to automotive to stationary. Such long life cycles include an extended initial phase until commercialization and much more a certain level of market diffusion is reached.

4.2 Opportunities and barriers for start-ups in the battery value chain

The fact that only very few start-up companies were founded in a period of steeply rising publishing and patenting activities seemed to be contradictory. The question arises, if this is a general pattern of the battery industry represented by the entire value chain or if there are specific hurdles at each step of the value chain. With respect to the entire industry, it must be pointed out that the market prices for lithium batteries have fallen dramatically over the last 10 years, which increases the entrance barrier significantly for start-up companies all along the value chain (Nykvist, Nilsson 2015). The cost for EV manufacturers for lithium battery cells fell by almost 14 % annually, from more than 1000 \$/kWh (kilowatt hours) down to less than 300 \$/kWh. More dramatically, the erosion of costs or achievable market prices for lithium battery cells was much faster than even the optimists would have predicted which made every business model based on such assumptions prone for failure. Despite not having confirmed data at hand, it sounds reasonable that the prices have even fallen more since the study has been published, and that when Tesla completes its so-called Giga factory in Nevada, United States, the market prices for cells will experience further pressure. It has been reasoned that the sharp decrease of prices for lithium battery cells is fuelled by a battle for market shares, production over-capacities and the entire industry reaching a large economy of scale. However, the result is that the prices in the market are so low that only large players with the according strength can enter the market for battery cells and their components. There are studies suggesting that the current costs for battery cells can only be achieved with factories producing several GWh (Gigawatt hours) of battery cells meaning an investment of billions of dollars (Ciez et al. 2017). Against this general background, a discussion of current barriers, recent developments in the battery industry and upcoming opportunities for start-ups at each step of the value chain seems to be worthwhile. The aim of the following analysis is to provide detailed reasoning for the imbalance of start-ups and R&D activity. Based on that, possible opportunities are derived, where start-ups could operate successfully in the battery value chain.

Materials

Only a few start-up companies dealing with the development and marketing of basic battery materials were found. This is somewhat surprising in view of the large number of scientific publications in this area. Many of them are dealing with the development of new materials for lithium ion batteries, trying to increase energy density or other performance parameters. In view of many innovative ideas in the scientific community, the further commercial development up to a product within a start-up company appears on first sight to be straightforward and ideal for founders. Saying that, economies of scale are driving the market for battery cells, which gives rise to the assumption that this cost sensitivity is transferred downstream in the value chain. E.g. only large materials suppliers will be able to reach price targets given by the cell manufacturers and small suppliers are stuck with niche cell producers, who may be able to afford higher costs for improved performance for the materials. On the other hand, the amount of material needed for the niche applications, hence the achievable business is not able to sustain the production and development costs of a start-up. Moreover, mass market battery cell producers depend on stable and reliable supply chains, which might be difficult to achieve when working with material suppliers in the start-up state. Therefore, lower in the value chain, the entry barrier for new players is very high as well, making it very difficult for start-ups to offer competitive products and services despite having superior properties.

Beyond the high pressure on price and costs in the industry, two more major hurdles may appear for small companies when developing materials for industrial customers: Firstly, long development times for developing a mature product, which require steady and high funding sources. As discussed, the life cycle of batteries spans over many decades indicating many years of development work before the introduction of new battery technologies. It appears straightforward that also the material development as the base of battery technology takes many years, which clearly imposes a hurdle for start-ups developing materials. Secondly, market access must be given in order to develop a sustainable business. Given that all major customers are Asian cell producers, needed intimate relations might be very costly and difficult to achieve for start-ups in the US and Europe. This is also reflected by the fact that most well-established materials suppliers are either large or Asian-based companies such as Umicore and Hunan Shansan for cathode materials, BTR New Energy and Hitachi Chemicals for anode materials, Shenzhen Capchem and Mitsubishi Chemicals for electrolyte materials and Asahi Kasei or Toray-BASF for separator materials. Their experience, market access and scale effects are hard to compete with. In addition, the majority of the chemical companies is focusing on their role as a supplier within the battery value chain, showing limited interest in forward integration with e.g. Evonik even backing out of their battery manufacturing activities in Germany. In view of the dominance of specialised chemical and electronics companies in the battery value chain (Golembiewski et al. 2015), the focus of start-ups on incremental innovations concerning the established LIB technology and thus directly competing with established players might pose exceptional challenges to successful market entry. In another aspect, the major cell manufacturers are suspected to have their own material development programs with which suppliers compete with and which makes it even more challenging for start-ups to find a profitable business. This aspect is supported by the large number of patents by cell manufacturers dealing with innovative materials concepts. In summary, due to the described path dependencies, it appears that the market for lithium battery cells has turned into a commodity market for big players with little space for start-up companies developing materials to enter. Therefore, start-ups should focus on potentially disruptive battery technologies beyond the established lithium battery.

Cell (components)

A lithium battery cell consists of several components including coated electrodes, separator and a mix of electrolytes and the can with the electrical connectors. There are also several complex process steps from materials to a complete cell. In most cases, the cell manufacturing is a highly integrated process including the production of electrode slurries, coating and processing of electrodes, filling the electrodes into cans, adding electrolyte, sealing the cell and an electrochemical formation step. With exception of the electrolyte mixing, most steps are usually developed by and integrated at the cell manufacturer, which makes it very difficult for start-ups to establish components or process innovation, because the cell manufacturer considers such technologies as their core competence. They allow only little insights into their processing and component development so that a start-up company has major challenges to offer a fitting and successful product or innovation. This explains why so few product launches and start-up companies were found at this point of the value chain.

To the best of our knowledge, no start-up is successfully working with such products and the reasons for that are still unknown. Obviously, the major cell manufacturers prefer to have all process steps for the cell production in-house. This could be caused by the complexity of the cell architecture and the complexity of controlling the quality of the components, which makes it very difficult to receive components from external sources and build them into cells. The failure of components can lead to catastrophic failure later when used by end-consumers. Saying this, the fast growing market for lithium-ion battery cells may motivate new producers introducing innovative processes for cell manufacturing. This could open the door for start-ups offering semi-finished goods like slurries and electrodes. Currently, it cannot be overseen how powerful or realistic this opportunity is. New players in the field face strong headwinds with respect to technology complexity and cost as well as price challenges, which may change due to undersupply of battery cells by sharply increasing demand.

Battery (system)

For most applications, several battery cells need to be assembled and combined with electronics components. For consumer electronics products, the battery cell integration always takes place at the electronics assembler, whereas due to the size and complexity the construction of a battery system for automotive and larger stationary applications can be a separate production and value step for start-ups. Indeed 20 product launches and 8 start-up companies were identified at this point of the value chain, which appears as a rather low number considering the myriad of potential applications for battery systems in the automotive or stationary storage markets. Several reasons might explain this finding: Firstly, to become a tier 1 supplier within the automotive value chain is rather challenging for a start-up, because the automotive industry follows specific standards and processes, which are a significant hurdle for small companies. Moreover, it can be reasoned that automotive companies would not base the development of such a key component on the success of a start-up company, but rather rely on their established suppliers. Indeed, the latter is observed in the market where tier 1 suppliers like Bosch, Continental or Dräxlmeir develop major components of the electric power train including batteries and battery modules for automotive OEMs.

Considering the intimate dependence of the battery system final device on the application, a close relation to the OEM seems to be a vital requirement for successful business development. It appears even that the application and the battery system must be developed side by side, which explains why the automotive OEMs all develop and even manufacturer their own battery systems either themselves or with their established tier 1 suppliers. This leaves very little space for start-ups. Moreover, the long timeframes in the established automotive industry and the large-scale requirements on the supply chain make the entry barrier for start-ups very high.

This might change with appearance of new players in the automotive world focussing entirely on EV. Tesla might serve as a prime example, challenging the automotive OEMs, but also companies like StreetScooter founded as spin-off of RWTH Aachen University and bought and further developed by the Deutsche Post AG exemplify that this part of the value chain is an attractive entry point for start-up companies. In addition, established automotive suppliers apparently have not built a thorough portfolio of technology competences concerning electric drives so far, which even broadens the opportunity for market entry for start-up companies (Borgstedt et al., 2017). In this context, it needs to be mentioned that these companies develop the battery system and the application side-by-side, which is analogous to the first developments of lithium batteries in the context of consumer electronics (e.g. Sony Camcorder).

Application

Start-up companies often find it challenging to assess the suitability of a battery (cell) for their specific application context. Whereas performance indicators like initial capacity and power are rather straightforward to determine, lifetime and reliability testing is costly and complex. This is of importance because the lifetime of the cell is closely related to the business case of the product and depends mainly on the mode of use by the end customer. The information by the battery cell supplier about lifetime can only refer to standard testing, which is only loosely related to real-life applications. In this context, start-ups with limited resources have an obvious disadvantage compared to large OEMs. Another current issue that start-ups in need of lithium battery cells face is the market availability of the respective battery system. In a two-digit growth market, the availability of cells of suitable quality might be a challenge, particularly when competing with OEMs and their massive buying power.

However, more powerful and less expensive battery technologies might be able to trigger new end-consumer products – applications – that were not possible to build before. Lithium batteries are tunable in their properties and therefore open up opportunities for a large variety of applications. Drones, power tools, electric bicycles or autonomous lawn mowers are such applications, which have seen a rapid development and marketing due to the availability of lithium-based battery technologies. Especially in the context of steeply falling prices for lithium-based battery technologies, start-ups have numerous possibilities to develop ideas for innovative applications, which desire high-energy or high-power battery technology. One example is the trend towards so-called "wearables" – electronic devices integrated in clothing including sensors for body functions like pulse and temperature (Preeti et al., 2017). Such applications need powerful battery technology to be useful for the end-customer. It also desires tailored battery solutions, which may well be an opportunity for start-ups in the field of battery cell development. The same applies for batteries for medical applications, which have quite a different set of specifications than commodity battery cells for which the outlined barriers for start-ups exist. This application field may go beyond the scope of this contribution, but might be indeed a promising area for start-up companies. It can also be stated that innovative batteries are an enabling technology giving rise to significant developments in many technology-driven areas. Side aspects like battery testing equipment or peripheral technology like thermal management solutions for batteries are outside the scope of the present study, but appear due to the strongly growing trend of the electrification of mobility an interesting playground for start-up companies. A summary of the barriers and opportunities for start-ups in the battery value chain is presented in Table 2.

Table 2 Barriers and opportunities for start-ups in the battery value chain.

	Materials	*Cell (components)*	*Battery (system)*	*Application*
Barriers	▪ Cost sensitivity ▪ Limited access to customers ▪ Long development cycles (> 10 years) ▪ High funding needs ▪ Competition with customer´s own material development	▪ Complexity of cell manufactu-ring process ▪ No acceptance of external sourcing of cell compo-nents by cell manufacturers	▪ Organizational and administrative barriers to become tier 1 supplier ▪ Critical mass needed before accepted to be a tier 1 supplier for automotive OEM ▪ Competition with OEM´s own battery production	▪ Battery performance testing costly and complex ▪ Availability of lithium battery cells
Industry developments	LIB as a commodity	New production processes for cell (components)	Emergence of more and more EV-only OEMs	More powerful and less expensive batteries open up new areas of application
Opportunities	Radically new high-energy materials beyond LIB	Semi-finished goods such as electrodes or slurries	Battery (system) assembly for EV-only OEMs	Applications beyond EV and consumer electronics

Despite highly dynamic R&D activities, technology transfer via start-ups is only taking place on a very limited level and differs with regard to the respective value chain steps. In terms of battery materials, the few start-ups active in this step find it difficult to compete with established players in the LIB market due to long development cycles and the required quantities and stable quality by cell manufacturers. Instead of focusing on incremental improvements of the established LIB technology, seeking for radical or disruptive battery technologies might be a more viable option for start-ups. Due to the integrated production of components and cells, we only found limited options for start-ups in this value chain step. It appears that low hanging fruits for start-ups are rather located higher in the value chain when integrating cells to battery systems and developing applications relying on innovative battery technologies.

5 Conclusions

The study at hand successfully introduces start-ups as an additional technology life cycle indicator to capture the transfer from R&D to industrial application, i.e. the early phase of application. This is particularly relevant in the battery industry, where R&D is closely intertwined with the respective applications. The subsequent analysis of opportunities and barriers for start-ups along the battery value chain shows that start-ups can be used best to foster battery technology transfer higher in the value chain when integrating cells to battery systems and developing applications relying on innovative battery technologies.

These findings provide theoretical implications for the life cycle analysis of sustainable technologies. Emerging sustainable technologies often struggle to cross the chasm between R&D and application because of established, more cost efficient technologies. Due to the largely environmental and societal benefits of sustainable technologies, a successful transfer is largely dependent on policy measures such as subsidies or quotas. Start-ups as indicator for the early phase of application refine sustainable technology life cycle analysis, which has focused on publications and patents for R&D as well as new product launches for application (Bornkessel, Bröring et al.

2016). The additional indicator allows detailed insights into the critical transition from R&D to application, where product launches might not be observable yet. In addition, sustainable technology forecasting literature is expanded by an application-centred perspective to complement the current R&D focus. This approach allows identifying transfer opportunities along the value chain and is particularly valuable for technological fields, where R&D and application are closely intertwined. Early information on possible and upcoming application fields is critical to successfully bring new technologies into the market.

With regard to practical implications, the study provides insights for multiple audience groups. Firstly, the results are interesting for start-ups and other players trying to gain momentum in the battery field. A better understanding of the hurdles for technology transfer in the battery value chain and helps identifying valuable starting points for start-up activities within the battery value chain. Secondly, because of the high societal, economic, and political relevance, the findings are equally important for political decision makers to accordingly shape and size funding programs. Targeted governmental support for technology transfer and start-up companies can contribute to close the gap between battery R&D and industrial application and value creation. Thirdly, we address practitioners in the field of technology forecasting. Start-ups as additional technology life cycle indicators provide them with an additional methodological toolbox for a more sophisticated analysis of technology life cycles.

Notwithstanding the valuable insights the study provides, there are some limitations to be mentioned. Although the technology life cycle relies on the often and sometimes wrongly criticized linear model of innovation (Balconi, Brusoni et al. 2010), it provides two striking advantages (Järvenpää, Mäkinen et al. 2011). First, the interactions between the different steps of the technology life cycle are clarified without unnecessarily complicating the model of innovation. Second, and in contrast to many further approaches, multiple indicators are used to prevent possible biases due to relying on solely one indicator. Despite the use of multiple indicators from different databases to depict the technology life cycle and careful selection of the respective search strings, a keyword-based search always bears the risk of including unsuitable elements and excluding suitable ones. These effects were minimised by performing plausibility checks, e.g. concerning IPC groups and assignees for patent analysis and subject areas as well as authors for publication analysis. In addition, detailed reasoning is provided for the selection of the respective databases. Nevertheless, further studies to use additional databases to broaden the empirical basis for start-up identification are highly encouraged.

The detailed insights in terms of technology life cycle and industry clockspeed in the area of lithium batteries provide an excellent starting point for further research in this field: Why there is no disruptive battery technology with industrial application? What are the barriers for technology transfer in the battery field? Why do battery start-ups fail and how does this depend on their position in the value chain? Future studies on life cycle indicators might want to have a closer look at the specific reasons for the large and persisting gap between R&D and industrial application, not only concerning batteries, but many other, often interdisciplinary, technological fields such as biotechnology or nanotechnology. Research endeavours could encompass case studies analysing the development of particular start-up companies or alternative mechanisms of technology transfer between science and industry such as technology parks to refine and extend indicators for the early phase of application.

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