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Policy Challenges Induced by Technological and Business Model Innovation

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Abstract

Technological change is occurring at an ever-increasing speed. Such technological progress is also accompanied by new business models, which often aim at benefiting from network externalities. With their special competitive dynamics, network industries, in particular, require the attention of scholars and (business) policy makers. Due to the unparalleled rapid diffusion of the constituting technologies, the digital economy has received growing attention. In parallel, the energy sector is undergoing a profound transformation where the fostering of sustainability remains an important challenge.

This dissertation sheds light on several important research questions in the above-mentioned context. Essay 1 analyzes innovation in electrochemical energy storage technologies using a patent-based approach. The novel Cooperative Patent Classification (CPC) is used to analyze the progress in several still-competing technologies for stationary energy storage. A strong surge in lithium battery patent applications has occured, which indicates that the introduction of improved modules will continue. Within this technology, Asian firms have a dominating position, which has significant implications for European car manufacturers.

Essay 2 analyzes the role of a firm’s knowledge network structure on different types of innovation using the empirical setting of the lithium ion battery industry. Indications are found that increasing knowledge decomposability is positively associated with modular product innovation, whereas increasing knowledge decomposability has an inverted U-shaped relationship with architectural product innovation.

Essay 3 investigates new business models and barriers in stationary energy storage, allowing a more efficient use. The research design consists of a cross-case study using expert interviews and document analysis. Models relying on the transmission of electricity from individual rooftop photovoltaics to a shared storage system through the public grid are facing significant

regulatory barriers. Removing these policy barriers would enable a more efficient use of electricity storage systems. By contrast, projects relying on a less regulated micro grid managed by the administration or strata entities of multi-household developments seem promising already under the current regulatory framework.

Essay 4 maps and measures the market capitalization of the digital economy in selected countries. The findings show that market capitalization is concentrated in certain districts, particularly located in the United States. For Germany, the results indicate that policy measures should be undertaken to ameliorate competitiveness in the field.

Essay 5 shows and discusses the consumer policy challenges arising from new data-driven business models based on current literature.

Based on the findings, implications for energy, innovation, and consumer policy are presented. In addition to sector-specific implications, the findings indicate that both sectors, the energy and the digital economy, increasingly intertwine. Particularly, the intersection of both will be an interesting and important arena for future research.

Kurzfassung (German Abstract)

Der technologische Wandel tritt mit zunehmender Geschwindigkeit auf. Er wird auch von neuen Geschäftsmodellen begleitet, die oft darauf abzielen, von Netzwerkexternalitäten zu profitieren. Wegen ihrer besonderen Wettbewerbsdynamik erfordern insbesondere die Netzwerkindustrien die Aufmerksamkeit von Wissenschaftlern und Entscheidungsträgern in Politik und Wirtschaft. Aufgrund der unvergleichlich schnellen Verbreitung der konstituierenden Technologien hat die digitale Wirtschaft zunehmend Aufmerksamkeit erhalten. Parallel dazu erlebt der Energiesektor eine tiefgreifende Transformation, und die Förderung der Nachhaltigkeit bleibt eine wichtige Herausforderung.

Diese Dissertation untersucht einige wichtige Forschungsfragen im zuvor erwähnten Kontext: Essay 1 analysiert die Innovation in elektrochemischen Energiespeicherungstechnologien mit einem patentbasierten Ansatz. Die neuartige Cooperative Patent Classification (CPC) wird verwendet, um den Fortschritt in mehreren noch konkurrierenden Technologien für die stationäre Energiespeicherung zu analysieren. Es wird ein starker Anstieg der Lithium-Batterie-Patentanmeldungen gefunden, was darauf hinweist, dass die Einführung verbesserter Module zu erwarten ist. Innerhalb dieser Technologie haben asiatische Firmen eine dominierende Position, die für europäische Automobilhersteller erhebliche Auswirkungen hat. Essay 2 analysiert die Rolle der Wissensnetzwerkstruktur eines Unternehmens auf verschiedenen Arten von Innovationen anhand von empirischen Befunden aus der Lithium-Ionen-Batterieindustrie. Es wird Evidenz dafür gefunden, dass die erhöhte Wissenszerlegbarkeit positiv mit modularer Produktinnovation verbunden ist. Daneben wird gezeigt, dass die Wissenszerlegbarkeit eine umgekehrte U-förmige Beziehung mit architektonischer Produktinnovation hat.

Essay 3 untersucht neue Geschäftsmodelle und Barrieren für die effizientere Nutzung stationärer Energiespeicher. Das Forschungsdesign besteht aus einer Cross Case Studie

basierend auf Expertengesprächen und Dokumentenanalysen. Die Befunde zeigen, dass Modelle, die sich auf die Übertragung von Elektrizität von einer individuellen Photovoltaik-Dachanlage auf ein gemeinsames Speichersystem durch das öffentliche Netz stützen, vor erheblichen regulatorischen Barrieren stehen. Die Beseitigung dieser regulatorischen Barrieren würde eine effizientere Nutzung von Stromspeichersystemen ermöglichen. Im Gegensatz dazu berichten Projekte, die sich auf ein weniger reguliertes Mikro-Netz stützen, weniger von Barrieren.

Essay 4 misst und kartographiert die Marktkapitalisierung der digitalen Wirtschaft in ausgewählten Ländern. Die Ergebnisse zeigen, dass sich die Marktkapitalisierung in bestimmten Bezirken konzentriert, vor allem in den Vereinigten Staaten. Für Deutschland zeigen die Ergebnisse, dass politische Maßnahmen zur Verbesserung der Wettbewerbsfähigkeit in diesem Bereich unternommen werden sollten. Basierend auf aktueller Literatur zeigt und diskutiert Essay 5 die verbraucherpolitischen Herausforderungen, die sich aus neuen datengetriebenen Geschäftsmodellen ergeben.

Auf der Grundlage der Ergebnisse werden Implikationen für die Energie-, Innovations- und Verbraucherpolitik vorgestellt. Neben den sektorspezifischen Implikationen zeigen die Ergebnisse, dass sich die Sektoren Energie und digitale Wirtschaft zunehmend verflechten. Besonders der Schnittpunkt von beiden wird ein interessantes und wichtiges Gebiet für die zukünftige Forschung sein.

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1. Introduction

While technological change has been occurring for centuries, the internet at the turn of the millennium and smartphones have significantly accelerated technological developments. Numerous novel technologies are emerging and challenge the competitive advantage of established professional specializations, firms, regions, and nations. Particularly strong economies of scale—and in some cases, near zero marginal costs (Rifkin, 2014)—are unfolding distinct competitive dynamics. As many developments are path dependent and self-reinforcing, the technological change can quickly lock in, and an early and thorough analysis by policy makers is therefore required.

Figure 1 gives an overview of current key technological areas and trends, as selected by the Organization for Economic Co-operation and Development (OECD, 2016, p. 79). This dissertation focusses on two broader empirical settings: The first three essays investigate developments in the empirical context of the "energy and environment." Similar to the OECD (2016), the federal German government views "sustainable economic activity and energy" as among the key fields of its high-tech strategy (Bundesregierung, 2014, p. 5). In this area, the essays focus particularly on **energy storage** technologies, as they are crucial for the decarbonization of both the electricity as well as the transportation sector. Within energy storage systems, particularly lithium ion batteries are becoming relevant, due to price improvements and increased production volume (IEA, 2017).

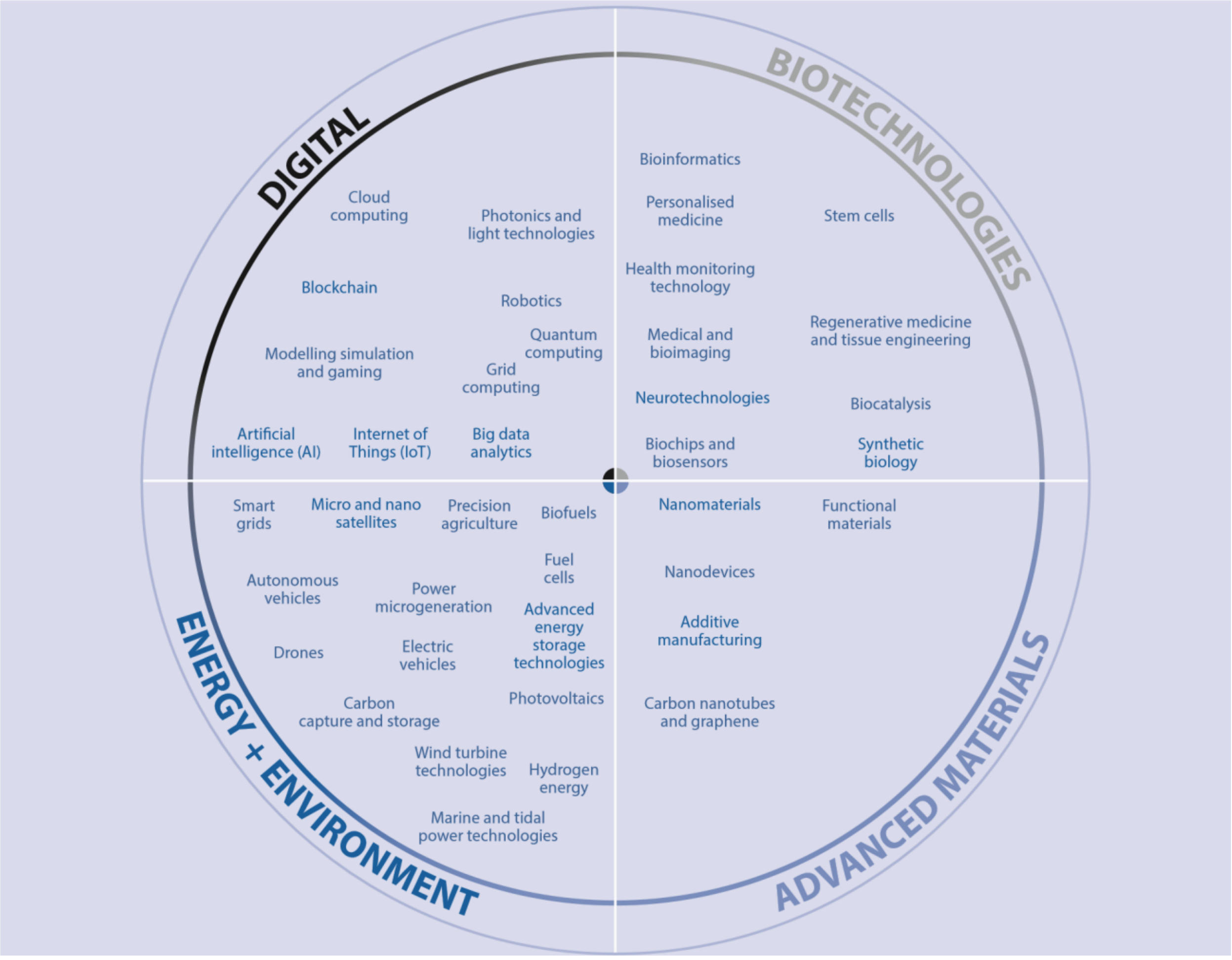

Figure 1. Key and emerging technological trends (OECD Science, Technology and Innovation Outlook 2016, p. 79 by OECD Publishing. Reproduced with permission of OECD Publishing in the format Thesis/Dissertation via the Copyright Clearance Center.)

At the same time, **digital technologies** have also been highlighted as one of the key fields by the OECD (2016) and have highest priority among policy makers in the public and private sector. For instance, similar to the above-mentioned challenges around sustainability, the “digital economy and society” has been selected as one of the key areas by the federal German government (Bundesregierung, 2014, p. 5). The digital economy is, in many cases, altering value chains or creating entirely new ones. In particular, the digital economy has created a new value chain around personal data (Bründl, Matt, & Hess, 2015). The interest of policy makers can be explained with the intent to establish a strong economy. However, big-data applications are also promising due to the potential improvements in several important areas of society (OECD, 2015b).

Analyzing both areas from a technological innovation perspective alone would be insufficient. In many cases, the technological innovations are also enabling novel business models. This is particularly true in the digital economy and the power sector. In the electricity industry, the possibility for decentralized electricity storage is an entirely new component in the power sector. Also, the digital economy is governed by technological and business model innovation due to the above-mentioned novel value chain around personal data. The notion that competition in the digital economy is shaped by both business model and technological innovation is also shared by Teece (2012). Business model innovations have the potential to increase efficiencies at markets, yet markets with network externalities can have the tendency to converge towards a few large players, thus raising questions about how they can be regulated (Azevedo & Weyl, 2016).

Next, to the direct benefit of a broad diffusion of the technologies in the above- mentioned areas, the interest of policy makers can also be explained by the fear of *creative destruction* (Schumpeter, 1950), i.e., that by not participating in these developments, their area of responsibility risks falling behind. Scholars, managers and policy makers are thus confronted with a plethora of questions in these areas: *How can progress in selected technologies be monitored and is its advancement sufficient for a transition towards a sustainable future? Are there better or even optimal ways of organizing knowledge resources to foster innovation? Is there a need to adjust the regulatory framework to allow the optimal use of technologies? Is the perception that some areas are falling behind in the digital economy justified? What are the implications of new digital technologies for consumer policy?*

This dissertation seeks to shed light on the above-mentioned research questions by addressing them in several essays. The remainder of this dissertation is organized as follows. Section 1.1

discusses the theoretical background, Section 1.2 introduces the employed methods and data. Chapter 2 contains the manuscripts of this dissertation. Publications that have already appeared in print are enclosed in the Appendix. Chapter 3 discusses the findings and concludes the dissertation.

1.1. Theoretical background

Innovation has been studied for several decades. In much of the 20th century, it was often associated with improved technologies, i.e., new products or procedures. The internet and related technologies have tremendously reduced search costs (Brown & Goolsbee, 2002) and collaboration efforts. This has been further accelerated by a second wave with the diffusion of smartphones, whose success has been attributed to the facilitation of the mobile experience of the Internet (West & Mace, 2010).

In parallel, during the last two decades, other types of innovation have been focused upon. The observation that firms are increasingly able to stay ahead of the competition because of improved business models enabled by improved technologies has attracted much interest. Consequently, students of innovation have argued that there are different types of innovation. Markides (2006, p. 19) distinguishes between “business-model innovations,” “technological innovations,” and “radical product innovations.” Also Baden-Fuller and Haefliger (2013) argue that it is reasonable to think about possible differences between business model and technological innovation, despite apparent interdependencies. The following sections will, therefore, discuss technological innovation and business model innovation in more detail.

1.1.1. Technological innovation

1.1.1.1. Characterization

Technological innovations are commercial activities based on novel technological developments. It is important to distinguish them from the mere invention (Hill & Rothaermel, 2003). While some inventions may lead to rapidly diffusing technological innovations, others may not work, for example, due to a lack of market potential or a lack of commercialization competencies or willingness.

Within technological innovation, Henderson and Clark (1990, p. 3) distinguish between “incremental,” “architectural,” “modular,” and “radical innovation.” To distinguish the four types of innovation, Henderson and Clark (1990, p. 12) argue within two dimensions: 1) the “Core Concepts,” as well as the "Linkages between Core Concepts and Components." Incremental innovation is generally understood as consisting of small, gradual improvements of existing technologies, which lead to an improved product. The efforts required to achieve this type of innovation can nevertheless be significant (Henderson & Clark, 1990). On the other hand, scholars and managers refer to radical innovations when a novelty is fundamentally different—in many cases, in both the technologies necessary for production, as well as their potential applications. Henderson and Clark (1990, p. 12) define architectural innovation where the central notions are “reinforced” but the relationships between the central parts are altered. By contrast, modular innovation is considered the opposite, i.e., it changes the central components, but leaves the relationships between them unaltered.

Next to this quadripartite definition, scholars have also argued for numerous other definitions. Garcia and Calantone (2002) have reviewed several studies in the area and highlighted the importance of clarification.

1.1.1.2. Innovation systems and knowledge networks

Not only entrepreneurs but also scholars and policymakers have been interested in fostering innovation for a long time. Many scholars consider the *recombination* of existing knowledge elements as one of the most important sources of innovation (Fleming, 2001; Yayavaram & Chen, 2015). Researchers have therefore aimed to understand the localization and structure of knowledge. On the firm level, knowledge networks have attracted the interest of management scholars (Nerkar & Paruchuri, 2005; Phelps, Heidl, & Wadhwa, 2012; Yayavaram & Ahuja, 2008).

Next to the structure of knowledge within organizations, inter-organizational networks have been addressed, as well. The innovation systems literature has studied the role of a variety of actors, institutions and systems. Significant attention has been given to innovation systems at the national level. This is particularly understandable, as innovations in certain sectors such as energy, can be strongly influenced by legislation. The framework of national systems of innovation (Lundvall, Johnson, Andersen, & Dalum, 2002; Nelson & Rosenberg, 1993) has been developed to describe the role of a variety of stakeholders involved in innovation.

While the framework of national innovation systems (NIS) has been used to explain differences between countries, the fertility of local entrepreneurship ecosystems, such as the Silicon Valley and Boston’s Route 128, has attracted researchers’ interest to clusters (Engel, 2015; Porter, 1998) and regional systems of innovation (RSI) (Doloreux, 2002). Other scholars have highlighted the role of sectors (Malerba, 2005) or technologies (Jacobsson & Bergek, 2004), for example, by employing a technological innovation system (TIS) perspective. Technological innovation systems consist of “actors,” “networks,” and “institutions” (Bergek, Hekkert, & Jacobsson, 2008, pp. 3-4). According to Jacobsson and Bergek (2004), TIS are manifested in the following steps: During the initial period, which may stretch over several decades, (product) components, policies, and markets are unclear but are gradually emerging. In the following development phase, changes still happen, but small adjustments can lead to increasing momentum and self-reinforcing dynamics.

While a significant portion of the innovation dynamics can be explained at the regional and national level, with the increasing role of international (knowledge) exchange, the reach of innovation systems is not limited to a national or local scope anymore. Binz and Truffer (2017) suggested studying innovation based on the perspective of global innovation systems (GIS), consisting of regional and national systems, which are linked by multinational corporations, non-governmental organizations, and international organizations for standardization.

1.1.1.3. Impact

While technological innovation often causes societal progress, it can also harm incumbents. The discussion about the potential impact on technological innovation can be traced back to Schumpeter, who coined the infamous term, “creative destruction” (Schumpeter, 1994, p. 81). Technological innovations threaten the very existence of established firms, as a significant reduction of the market share can endanger the survival of incumbents.

Ansari and Krop (2012) reviewed and synthesized numerous studies regarding the effect of radical innovation on established firms. They set the results in the context of both, technological and business model innovation. Researchers and practitioners have discussed a reduction in firm life expectancy, for example, measured in the average number of years firms of a given year stay listed in the Standard & Poor’s 500 (S&P 500) index. Foster and Kaplan (2001) (as cited in Stubbart & Knight, 2006) found that the annual turnover rate has increased during the last century and that the lifespan went down to less than 15 years. While Stangler and Arbesman (2012) found that extreme reductions in the life expectancy can also be attributed to M&A-related changes, they indeed found an increased turnover rate within the S&P 500. Concerning the question whether firms can escape their trajectories, McKinley, Latham, and Braun (2014, p. 88) argued that innovations can lead to a “turnaround” if they are adjustable, i.e., can be fitted to the organization. The notion that incumbents can also succeed in mastering technological change is also shared by Bergek, Berggren, Magnusson, and Hobday (2013), who describe based on empirical insight how established firms react to such challenges. However, Josefy, Harrison, Sirmon, and Carnes (2017) noted that discrepancies remain in the predictions of the ideal moment for innovation within existing firms.

The adverse effects of losing in the technological race are becoming apparent in regions such as Detroit or the Ruhr area, which both were once important industrial centers but later experienced an economic decline after the demand for their products and goods weakened. These regions highlight that firm survival is not only a question for investors and employees (Josefy et al., 2017) of firms but for everyone concerned about societal welfare.

Next, regarding the question of consequences for incumbent firms, there are also important issues regarding the effect on the innovating firm. Numerous studies have investigated from different perspectives how innovating firms can benefit from the innovations. The major risk for innovating firms is that potentially high costs and investments for R&D cannot be appropriated because imitators build upon the work and rapidly gain market share. The profiting from innovation framework by Teece (2006) has established factors and capabilities that are necessary for entities if they want to capture value from technological innovations. According to Teece (2006, p. 1136), next to trade secrets and copyrights, patents and trademarks are valuable assets for benefitting from commercialization. The latter two are intellectual property rights, for which the inventors or their organization must apply. The subsequent publication of the application and granted title in databases opens the way for measurement of technological innovations, which is explained in more detail in the methods and data Section 1.2.1.1.

1.1.2. Business model innovation

1.1.2.1. Characterization

Business models are essential for companies to capture value from technological innovation. In fact, without a suitable business model, technological innovation has little value for firms (Chesbrough, 2010). There are numerous literature streams regarding the business model definition. In their review, Massa, Tucci, and Afuah (2016, p. 73) have argued that the different streams understand business models as “attributes of real firms,” “as a cognitive/linguistic schema,” or “as formal conceptual representations/descriptions." A notable example of a business model definition is the one by Osterwalder and Pigneur (2010). It consists of nine parts, namely (Osterwalder & Pigneur, 2010, pp. 16-17): “customer segments,” “value propositions,” “channels,” “customer relationships,” “revenue streams,” “key resources,” “key activities,” “key partnerships,” “cost structure.” Massa et al. (2016) concluded the review of the business model literature by highlighting challenges in the area of business model research for sustainability particularly. They noted that particularly in the area where the value creation benefits multiple stakeholders, further research is to be undertaken. The importance of shedding more light into the value creation process for several stakeholders has also been highlighted by S. Hall and Roelich (2016).

Business model innovation can help to utilize resources more efficiently (Azevedo & Weyl, 2016). Cramer and Krueger (2016) compared the “capacity utilization rate” of Uber with traditional taxi companies and showed that Uber leads to an improved efficiency. In San Francisco for example, the ratio between the time where a driver has a passenger on board out of the total working hours is 38.4 and 54.9 for Uber drivers (Cramer & Krueger, 2016, p. 179).

Business model innovation can also be accompanied or introduced by technological innovation. Baden-Fuller and Haefliger (2013) give the example of Google’s core product, the search engine, which provided technologically improved search processes that at the same time benefited from an innovative business model based on advertising. Another notable example of business model innovation based on digital technology is cloud-based computing services. It cannot be neglected that technological improvements such as optimized computing resources and faster Internet connections enabled the diffusion. Most importantly, however, renting software, platform, or infrastructure as a service (SaaS, PaaS, Iaas) rather than selling the products to commercial customers was a business model innovation that proved as very successful for the numerous firms such as Amazon, Microsoft and Salesforce. The availability of large computing resources quasi-instantaneously has found many users among businesses. For startups, the seamless scalability, from a single server to large computer farms, has helped in the rapid growth of many businesses. While in earlier days, new computing centers had to be planned several months or years in advance, they are nowadays available within a few clicks.

1.1.2.2. Antecedents

While much of the innovation systems literature mentioned in Section 1.1.1.2 has been developed in the study of technological innovations, many factors that support technological innovation are equally helpful in supporting business model innovation. Next to the promising applications and value propositions of novel, data-driven business models—as for example outlined by the OECD (2015b)—digital business models attract investors from the private sectors due to the prospect of a high return on the investment for successful business models, as the network externalities (explained in more detail in Section 1.1.3.1) lead to changing competition dynamics.

In many cases, particularly data-driven business models, such as social media or other online platforms, a significant diffusion is necessary for the models to be viable. This usually requires fast and substantial initial investments, in order to stay ahead of the competition before network externalities support the maintenance of the business. Many of the prominent recently founded tech firms, therefore, relied on venture capital in an early stage. Initial public offerings (IPO) or the sale of their stakes to larger companies has given the founders capital to invest in other novel firms, such as the investment of Jeff Bezos in Google shows. The availability of venture capital is thus an essential antecedent in supporting business model innovation by new firms. The example also shows that such ecosystems have a self-reinforcing effect, i.e., start-ups have the best chance for growth if they are surrounded by founders and capital of previously successful ventures, making the imitation of ecosystems so difficult.

Next to innovation from start-ups, researchers have also been interested in the antecedents for business model innovation in existing firms. Martins, Rindova, and Greenbaum (2015, p. 102) mention that business model innovation primarily happens due to "changes in technology or regulation," but that also cognitive methods can be used to induce business model innovation. The understanding that business model innovation is often enabled by technological innovation also for existing firms is supported by Waldner, Poetz, Grimpe, and Eurich (2015). They found that for existing firms, the introduction of novel business models is positively correlated with the recent introduction of novel products or procedures in the firms. Often, before a viable novel business model in an established firm is found, significant trialing is necessary. A barrier to business model innovation can also be given by insufficient resource allocation, e.g., when managers are not willing to shift resources from the old, proven, business model towards the new.

1.1.2.3. Impact

As discussed in Section 1.1.2.1, business models are essential for firms to thrive. It has been shown that the business model design has a significant effect on the performance of companies (Zott & Amit, 2007). Innovation concerning the business model can, therefore, be a major differentiator.

Similar to technological innovations, firms offering services or products based on innovative business models can capture significant shares of the market. A contemporary example is Netflix, whose rise has been made responsible for losses in the numbers of traditional cable TV subscriptions (Spangler, 2016; Vranica & Ramachandran, 2015).

Section 1.1.1.3 discussed the impact of technological innovation and how the innovating firm can benefit from its novel developments. For business model innovation, elements of the benefiting from innovation framework do not maintain their significance in all cases. This can be seen by the example of patents. Especially for platform-based business model innovations, network externalities and the control over the platform are important to uphold the chance to benefit from the innovation. These have their unique challenges, which are discussed in the following section.

1.1.3. Policy challenges and derived research questions

Policy challenges are only given in cases where regulatory action is justified. Stiglitz (2010, pp. 2–6) argues that three reasons warrant governmental intervention: "conventional market failures," "irrationality," and "distributive justice." Conventional market failures can particularly occur when externalities are present. This can be the case in industries with network effects or the case in industries, which support the emergence of platforms. Platforms have their challenges, which are discussed in the following Section 1.1.3.1.

1.1.3.1. Digital platforms

Economies of scale, which give advantages to larger entities, have challenged policymakers for decades. More specifically, supply-side economies of scale have supported the emergence of large conglomerates such as General Motors, General Electric, Exxon Mobil, Panasonic and Sony, as well as many more. The tendency towards concentration has required policy makers to counter the establishment of monopolies. In parallel, some firms also benefited from products enabling demand-side economies of scale, i.e., direct network effects (Gawer, 2014). A classical example for direct network effects is the usefulness of telephony services, which directly increases growth in the number of users that can be contacted (M. Katz & Shapiro, 1985). A second, relevant effect are demand-side economies of scope, i.e., indirect network effects (Gawer, 2014). An example for demand-side economies of scope are software platforms, where an increased number of users makes it attractive for software developers.

The network externalities have led to a rapid growth of firms that can leverage them based on innovative technologies and business models. A notable example is Google, which became the most valuable firm (at least on one day), less than 18 years after its founding (Levy, 2016). The strong, monopoly-like market shares obtained by certain services have also raised suspicion of potential abuse and have triggered investigations, for example, at the EU level (e.g., Europäische Kommission, 2015). They have also invited broader attention to the topic and prompted discussion of the need for regulatory intervention and available instruments (Ballon & Van Heesvelde, 2011). Indeed, Zhu and Iansiti (2012) showed that competitors with products of superior quality can be kept out of markets with network effects by incumbents with a strong position. Particularly, technological areas with strong network externalities are challenging policy makers, as they seldom lead to market failures and thus require regulatory action.

In order to enable data-driven decisions, knowledge of the digital economy is essential. In such, the Commission of Experts for Research and Innovation (2014, p. 1) has raised the important research question, “*Can the emergence and dynamics of new digital business models be measured empirically over time and in international comparison?*” This question is addressed in more depth in Essay 4. Furthermore, the digital platforms have their value due to the large number of consumers with whom they are interacting. In fact, many of the business models rely on gathering and evaluating data of end users (see the essay of Section 2.5). Essay

5, therefore, addresses the implications of new digital business models on consumer research and policy.

1.1.3.2. Fostering sustainability in the energy system

In cases where the desired technological developments have not yet taken place, a market failure reasoning has been applied to justify support for R&D in the private sector (Martin & Scott, 2000). However, not all scholars agree that market failures in the innovation system are sufficient to justify innovation policy intervention (Bleda & Del Rio, 2013). Bleda and Del Rio (2013) discussed the systemic failure logic as a justification as an alternative to the market failure reasoning and conclude that it is generally more valid.

Indeed, the energy system, with its often large conglomerates that have often benefited from strong network externalities, has been inert concerning innovation towards a more renewable energy supply. To induce change, many countries have introduced feed-in-tariffs in order to increase the ratio of renewable energy. With increasing shares, however, the intermittency of renewable energies has become progressively problematic. Of particular interest for the candidates regarding potential solutions is energy storage, as it “is very much the key to unlocking the door of renewable energy” (P. J. Hall & Bain, 2008, p. 4352). There are numerous energy storage technologies, all of which have specific advantages and disadvantages regarding maturity, techno-economic parameters, efficiency, or geographical requirements. Batteries offer flexibility and scalability similar to distributed generation, from small scales up to 100 MW, and are therefore a promising candidate. Yet, costs still have to come down and at the beginning of the work on this dissertation, the leading technology to do so had yet to be found (Battke, Schmidt, Grosspietsch, & Hoffmann, 2013). Which technology should be pursued has not only been a question for energy and research policy, but also of strategic importance for firms (Eggers, 2014). Regarding policy support to facilitate the development of suitable technologies, there are two notable options. First is to introduce technology push measures, i.e., introducing government or other support for technologies in the area. An alternative would be demand-pull measures, such as feed-in-tariffs or the Kreditanstalt für Wiederaufbau (KfW)'s energy storage scheme, which increase the demand for a certain technology. As both measures have their distinctive advantages and disadvantages, recently, a mix of both have come into focus (Costantini, Crespi, & Palma, 2017; Ossenbrink, 2017). To enable informed decision making, numerous research questions need to be answered. The necessity to monitor innovation in electrochemical energy storage leads to research question 1: *How can progress in selected technologies be monitored will advancement be adequate for a transition towards a sustainable future?* This is carried out in the essay of Section 2.1, with methods that are discussed in Section 1.2.1.1. Due to the intricate "knowledge creation" in the lithium battery industry (Stephan, Schmidt, Bening, & Hoffmann, 2017, p. 713), this question also provides a valuable empirical context to investigate more general questions regarding innovation. Additionally, research question two can be raised: *What is the influence of a firm's knowledge structure on different types of innovation?* This question is answered in the essay in Section 2.2.

Next to achieving technological improvements, of equal importance is determining how these novel technologies can be integrated into existing or new markets. Particularly in a highly regulated industry such as the power sector, this question needs to be addressed not only by market entrants, but also by public policy makers. Since the regulatory framework around energy storage is still in an early stage, research question number three is raised: *Is there a need to adjust the regulatory framework to allow the optimal use of certain technologies?* By using the methods explained in Section 1.2.2, the research question is analyzed in Essay 3.

1.2. Methods and data

Technological innovations are often based on technical inventions. These can be protected by patents and other government granted exclusive rights (Markides, 2006). Thus, patents are also often used to protect and publish technological inventions. This fact is employed in Essays 1 and 2, which use measures based on patent data. The patent data-based methods are explained in more detail in Section 1.2.1.1.

Also, for Essays 3 and 4, which are business model innovation-oriented, patents have been considered as a measurement technique. However, it is harder to protect business model innovations.[1] While it is possible to some extent, it rather pertains to parts of the business models, i.e., business methods or processes rather than the model in general (Desyllas & Sako, 2013). Business process patenting has received increasing attention after Amazon’s efforts with the one-click patent (Ovans, 2000), which was later rejected in Europe (Jeitschko, 2015) and Canada (Crowne-Mohammed, 2010). Wagner (2008) mentioned a more restrictive examination of business method patents by the European Patent Organization compared with the United States Patent and Trademark Office. Recently, “the Alice decision” also led to a reduction of business method patent applications in the US (Loney, 2015, p. 1). These policy differences have resulted in temporally and spatially varying propensities to patent business methods. In such, it would be difficult to derive reliable measurements regarding businesses’ innovativeness in the area of business methods merely based on patent counts.

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[1] Parts of this paragraph have also been mentioned by the author in (Müller et al., 2016).

1.2.1. Secondary data analysis

With exponentially increasing storage capacities and data availability, pre-existing data is an increasingly likely scenario and makes the collection of primary data redundant for some research questions. Big data sets are opening up new ways for research in economics (Einav & Levin, 2014) and management studies (Tonidandel, King, & Cortina, 2016). One of the main advantages of secondary data analysis is that it is a comparably efficient research method (Brewer, 2012). In cases where previous research has already employed the data sources, such as in the case of the Thomson ONE and Patstat databases, another advantage is the reliability of the method. In some other cases, particularly in the case of country-level analysis, a full collection of data would often not be possible and, where commercial providers already offer similar data sets, often uneconomical. Nevertheless, research involving secondary data is not without obstacles. Secondary data has to be checked for consistency and accurateness (J. A. Katz, 1992). It also sometimes fails to encompass all items of interest to the researcher for a particular study.

For secondary data analysis in this dissertation, two types of data have been employed: First, patent data and second, financial data. Both are discussed in more detail in the following section.

1.2.1.1. Patent data

It is common practice within the science community to measure technological innovation via patent publications (Lee & Lee, 2013). Essays 1 and 2 are based on the analysis of secondary patent data. Of course, even this research approach has limitations. As written above, not all technological innovations are patented, and not all patentable inventions lead to technological innovations. However, there are technological fields for which there is a high propensity to patent new inventions. For battery technology-related fields such as electrical engineering, chemistry, and nanotechnology, patents are a good proxy. This contrasts with software, for example, or business methods where the patent approval processes differ significantly between legislations.

Essays 1 and 2 rely on patent data. Patent data was drawn from the PATSTAT database. The PATSTAT database is a product offered by the European Patent Organization (EPO) in bi-annual updates. PATSTAT has been accredited for having facilitated one of the “greatest advances in the field” of innovation research (Feldman, Kenney, & Lissoni, 2015, p. 1629). It is frequently used and best practices are constantly developing (Kang & Tarasconi, 2016). It contains the most important data attributes such as application numbers, dates, priority dates, family numbers, inventors, applicants, titles, and abstracts, as well as many other bibliographic entries for patent applications and patents from all major patent offices worldwide. The data is provided as bulk data, which can be fed into a (My)SQL-server. This enables processing of the whole data set, which for some attributes, contains more than 74 million entries (De Rassenfosse, Dernis, & Boedt, 2014, p. 396).

To derive relevant patents for Essays 1, we relied on the recently introduced Cooperative Patent Classification (CPC) (United States Patent and Trademark Office, 2013) classification. The advantage compared to a keyword-based search is that the categorization for a certain technology is carried out by trained professionals at the patent authorities. The Cooperative Patent Classification has been developed in a joint effort between the EPO and the USPTO, the process of which has also been analyzed by do Canto Cavalheiro, Joia, and Van Veenstra (2016). Compared to the older International Patent Classification (IPC) system, the CPC has noteworthy advantages for our purposes. First, it contains more entries than the older system. Second, it contains a new section Y, which allows the identification of new technological developments. Within this section, particularly class Y02, which covers technologies to counter climate change (Veefkind, Hurtado-Albir, Angelucci, Karachalios, & Thumm, 2012), contains patents relevant for our study. The CPC is receiving attention for landscaping studies also in other scientific disciplines, such as pharmacology, for example (Demidov, Currie, & Wen, 2017).

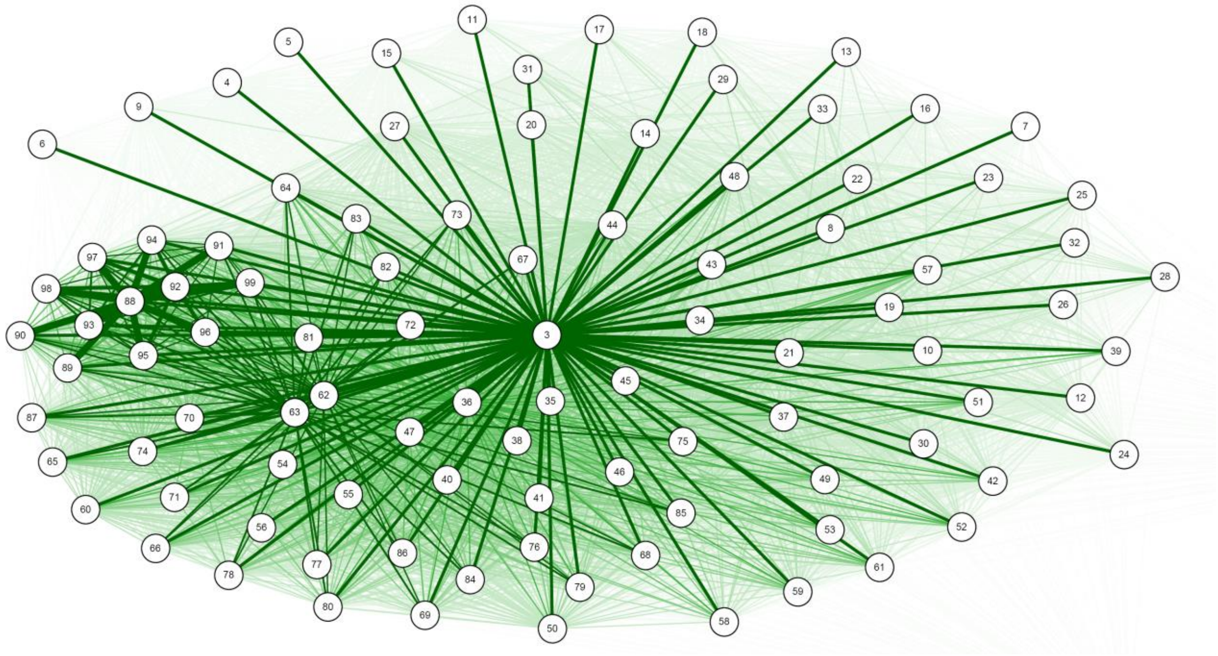

Figure 2: Exemplary knowledge network for a firm in one year (Two loosely tied nodes have been cut off for illustration purposes).

The technology classes were also relevant for the research in the essay presented in Section 2.2. The knowledge network of a firm in a given year was defined following Yayavaram and Ahuja (2008), where the nodes were the technological classes and the edges were given by patents filed in both classes. The illustration of an exemplary knowledge network consisting of 100 different subclasses is shown in Figure 2.

For the calculation of the decomposability, a modified clustering coefficient for every firm-year network was calculated. The clustering coefficient for a network is the mean of the clustering coefficients of all nodes of a network. Here, we used a C++-code, which was provided by Yayavaram and Ahuja (2008).

1.2.1.2. Financial data

The perception that traditional measures of economies, such as the gross domestic product (GDP), is not fully appropriate to quantify the dynamics of the digital economy that has also reached the realm of public debate (Hoffmann, 2017). This is because the summation of revenues of goods sold is not fully applicable to the digital economy. GDP and similar measures are not "invariant" to the selection of different business models (Coyle, 2016, p. 5).

Many of the leading and comparably young digital firms choose to reinvest their revenues in the first years; because of this, they did not report significant earnings. Comparing firms only by earnings would therefore not fully capture the dynamics of the digital economy. Due to the strong network externalities mentioned in Section 1.1.3.1, some companies also choose to operate free at first to achieve a strong growth in the user base, and only later increase fees to generate earnings. Valuating these companies only by revenues would thus lead to a significant underestimation. By contrast, market capitalization has the advantage that the market already accounts for foreseeable events in the future. We, therefore, relied on the market capitalization as a unit to measure the emergence of business models in the digital economy.

Similar to the innovation research as in the essays of Sections 2.1 and 2.2, relying on a classification system has significant advantages regarding reliability and reproducibility over other approaches. We, therefore, chose an industrial classification-system based selection (SIC, NAICS) to derive the sample used for Essay 4. After determining the firm sample, the data was drawn from ThomsonONE Investment Banking and Thomson Reuters Spreadsheet link.

As all other research, the research presented in the essay in Section 2.4 is not without limitations. First, due to data availability, it only includes public companies. Future research should also look at data from privately owned firms, for example building up data from Orbis. Additional research could also distinguish between different business units of conglomerates, i.e., not only differentiate at the level of the primary classification of a firm.

1.2.2. Document analysis and expert interviews

Unlike technological innovation, business model innovation cannot be measured as easily using patent counts. For Essay 3, qualitative research has therefore been chosen, as we were investigating a comparably novel phenomenon. Qualitative research is a particularly suitable approach for areas that have not yet been investigated in detail (Strauss & Corbin, 2015). Case studies are a valuable research method, for both theoretical and practical research. Cross-case studies are a valuable tool for theory building (Eisenhardt & Graebner, 2007) and at the same time, gain increasing recognition for research that is relevant for practitioners (Osterloh, 2016).

A cross-case study design was used, as it is considered more robust than a study built on just one case (Eisenhardt & Graebner, 2007). A further advantage is that it facilitates a cross-case synthesis, leading to additional results (Yin, 2014). A document analysis followed by expert interviews has been chosen. This is in accordance with Devine-Wright et al. (2017), who suggested document analysis followed by expert interviews as a suitable methodology to study markets and innovation for the case of energy storage. Both documents and interviews are suitable techniques for case studies (Yin, 2014). Similar to other research techniques, both have specific pros and cons. Bowen (2009) mentions numerous advantages of document analysis as a research technique: Documents typically offer wide-spanning reporting, precision, and solidity. Furthermore, important advantages of document analysis are that it is typically inexpensive, the analysis and collection often leave the measured entity uninfluenced, and the documents are obtainable in many cases (Bowen, 2009).

After the sample was finalized, materials from websites, technical (web-)magazines, presentations, scientific publications, corporate reports, and research reports were collected. We also searched for newspaper articles in specialized databases such as Factiva and WISO. For the next step, we searched for videos on online video platforms and TV stations. Videos were downloaded and transcribed. Subsequently, as recommended by Mayring (2011), a reduction step was undertaken, and paragraphs of pages of documents that didn’t cover the investigative projects were removed. A similar procedure was undertaken with the videos, which were cut to the relevant sections and afterwards transcribed. We used the qualitative data analysis MAXQDA to organize and evaluate the documents.

After an initial sighting and first coding of the material, an interview guide was developed. The guide consisted of a short introduction on the purpose of the survey followed by opening questions regarding the person’s background, responsibility, and experience in the project. First, this should reduce initial reluctance to respond and get a conversation going. Second, it also ensured that we were indeed talking to experts in the field. A block of questions on the business model was followed. It began with an open question on a potential business model that could be generalized out of the project. Following were questions on all nine business model components according to Osterwalder and Pigneur (2010). For some of the key business model components, we asked more detailed sub-questions.

At the end of the block, there was once again an open question where participants had the chance to annotate anything which they deemed relevant. The block on business models was followed by a block on barriers, where we also first asked an open question and then systematically probed it following the framework given by Painuly (2001). Interviews were recorded and later transcribed. The transcripts were included in MAXQDA next to the other documents.

2. Essays

An overview and the status of the essays included in this dissertation is given in Table 1.

Nr.	**Authors**	**Title**	**(Target) Journal or Edited Volume**	**Status**	**Digital Object Identifier (DOI)**
1	Müller, S. C., Sandner, P. G., & Welpe, I. M.	Monitoring innovation in electrochemical energy storage technologies: A patent-based approach	Applied Energy	Published	10.1016/j.apenergy.2014.06.082
2	Namkung, S.* Müller, S. C.* (* these authors contributed equally)	A firm's knowledge structure and its distinctive impact on the types of product innovation	Academy of Management Annual Meeting Proceedings	Abridged, earlier version published; attached revised version in preparation for journal submission	10.5465/AMBPP.2017.262
3	Müller, S. C., & Welpe, I. M.	Sharing electricity storage at the community level: An empirical analysis of potential business models and barriers	Energy Policy	Published	10.1016/j.enpol.2018.03.064
4	Müller, S. C., Bakhirev, A., Böhm, M., Schröer, M., Krcmar, H., & Welpe, I. M.	Measuring and mapping the emergence of the digital economy: A comparison of the market capitalization in selected countries	Digital Policy, Regulation and Governance	Published	10.1108/DPRG-01-2017-0001
5	Müller, S. C., & Welpe, I. M.	Digitale Welt	Verbraucher-wissenschaften	Published	10.1007/978-3-658-10926-4_14

Table 1 Overview and status of publications included in this dissertation

2.1. Essay 1 – Monitoring innovation in electrochemical energy storage: A patent based approach

Full reference:

Mueller, S. C., Sandner, P. G., & Welpe, I. M. (2015). Monitoring innovation in electrochemical energy storage technologies: A patent-based approach. *Applied Energy, 137*, 537-544.

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.

Author contributions:

S.C.M. is the first author of this publication; the other authors are contributing authors. S.C.M. developed the research question and design, supervised by P.G.S. and I.M.W. S.C.M. carried out the data collection and analysis, in the initial stages supported by P.G.S. S.C.M. wrote the manuscript with suggestions and feedback from P.G.S. and I.M.W. S.C.M. carried out the submission process and correspondence.

2.2. Essay 2 – A firm's knowledge structure and its distinctive impact on the types of product innovation[2]

Reference of abridged publication:

Namkung, S.,* & Müller, S. C.* (2017, August). A New Venture's Knowledge Structure and Its Distinctive Impact on the Types of Product Innovation. *Academy of Management Annual Meeting Proceedings*. doi:10.5465/AMBPP.2017.262

(* these authors contributed equally)

Abstract:

A firm's innovativeness is driven by the structure of its knowledge base. Elaborating on this argument, this study examines the effect of the level of knowledge decomposability in a company's knowledge base on two types of product innovation – modular and architectural. The main argument of this study is that the level of knowledge decomposability distinctively affects these two types of new product innovation. We test our hypothesis with data on worldwide Lithium-Ion Battery (LIB) cell manufacturing companies between 1991 and 2013. Our analyses suggest that increasing knowledge decomposability is positively associated with modular product innovation, whereas increasing knowledge decomposability has an inverted U-shaped relationship with architectural product innovation. By distinguishing between these two types of newly developed products, this study extends the burgeoning literature on how the structural patterns of a company's knowledge base can affect its product innovation (Guan & Liu, 2016; Wang, Rodan, Fruin, & Xu, 2014).

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[2] An earlier version of this paper is also included in the dissertation of Namkung (2016)

Author contributions:

S.N. and S.C.M. are both leading authors of the paper. Both authors wrote the manuscript. Both authors carried out the data collection: More specifically, S.C.M. calculated the knowledge structure related variables and S.N. collected the dependent variables. Both authors jointly carried out the statistical analysis. S.N. handled the submission process and correspondence.

A Firm’s Knowledge Structure and Its Distinctive Impact on the Types of Product Innovation

1. Introduction

Due to the prospect of unlocking additional potential for technological advances, there is growing interest in the role of a company’s knowledge base in innovation. Previous research has mainly concentrated on the attributes of a company’s knowledge base, including knowledge size, depth, and diversity, as well as the degree of relatedness with other firms’ knowledge bases, as key drivers for firm innovation (Ahuja & Katila, 2001; Katila & Ahuja, 2002; Phelps, 2010; Wu & Shanley, 2009; Yayavaram & Ahuja, 2008). Yayavaram and Chen (2015, pp. 377-378) have described a company’s knowledge base as “the set of knowledge elements that it possesses and the relationships that it has forged between the knowledge domains to which these elements belong.” With this network analogy, the relationships among the elements within a company’s knowledge base may be more crucial than the attributes of its knowledge base. These connections “can serve as a medium of knowledge flow” and, as a result, enhance firm innovation (Guan & Liu, 2016, p. 108).

While studies have discussed and investigated links between the organizational and product structure (Argyres & Bigelow, 2010; Cabigiosu & Camuffo, 2012; Furlan, Cabigiosu, & Camuffo, 2014; Ulrich, 1995), the research on knowledge bases has given less consideration to the fact that the structure of the company’s knowledge base itself can influence firm innovation. Thus, the structural aspects of a company’s knowledge base need to be fully understood as another key driver for firm innovation. In responding to this call, a burgeoning stream of literature has examined how the structural properties of a company’s knowledge base spur innovation (Guan & Liu, 2016; Wang et al., 2014; Yayavaram & Ahuja, 2008; Yayavaram

& Chen, 2015). However, given that the type of firm innovation can vary – being either incremental, modular, architecture, or radical (Henderson & Clark, 1990) – the next important step is to uncover whether and how the structural patterns in a company's knowledge base have differential impacts depending on the types of innovation. Therefore, the research can be advanced through richer categorization of firm innovation by introducing two additional types – modular and architectural. These two types of innovation are more prevalent in the early stages of technological life cycles, where firms compete for successful products by experimenting with many different technologies. This is because, at this phase, the successful commercialization of new products requires the firm to synthesize the introduction of new component technologies (Magnusson, Lindström, & Berggren, 2003).

The goal of the present manuscript is to extend this stream of literature by investigating the differential effect of a firm's particular structural pattern – knowledge decomposability – on two types of firm innovation – modular and architecture – in an emerging high-tech industry. We chose to concentrate on the decomposability of a company's knowledge base rather than other dimensions such as cohesiveness, small-world, centralization, or hierarchy (Rivkin & Siggelkow, 2007) because knowledge decomposability reflects a firm's beliefs about which knowledge components should be combined and, conversely, which do not need to be combined. Moreover, given that these beliefs mainly reside in firms' experience before entering an emerging high-tech industry, the level of knowledge decomposability can also lead to differences in firms' ability to combine knowledge components for new product development.

The core argument of this manuscript is that the increasing decomposability of a company's knowledge structure is positively associated with modular product innovation, whereas the increasing decomposability of a company's knowledge structure has an inverted U-shaped relationship with architectural product innovation. We tested our theory and hypotheses on a rich merged dataset of patents and Lithium-Ion Battery (LIB) cell products in the context of global LIB cell manufacturing firms between 1991 and 2013, representing the initial phases of the industry life cycle (Wagner, Preschitschek, Passerini, Leker, & Winter, 2013). By investigating the differential effect of a company's knowledge structure on the types of product innovation, this study advances a burgeoning literature that investigates how the structural patterns of a company's knowledge base affect its innovation.

2. Theory and hypotheses

We apply a network analogy to firm knowledge structure and treat knowledge as a complex and multi-dimensional system in which knowledge components are embedded, rather than as a simple attribute of products. A company's *knowledge network* can be defined by considering the *knowledge components* as *nodes* and the combinations of two in inventions as *edges*.(Carnabuci & Bruggeman, 2009). Because innovation arises from combining or recombining knowledge components (Schumpeter, 1934; Weitzman, 1998), knowledge components are not independent but are interconnected through joint applications in previous inventions (Fleming, 2001). Thus, we concentrate on a firm's total knowledge structure and how it leads to new products, rather than on a certain piece of knowledge about a single product or product category (Yayavaram & Chen, 2015).

Among the structural features of a company's knowledge base, examining decomposability is important, because this dimension highlights the fact that even two firms possessing the same elements of knowledge may still differ in their capability to benefit from it. Several possible structural patterns delineate a continuum ranging from highly decomposable to nearly decomposable to non-decomposable (also known as integrated). In a highly decomposable knowledge base, the ties between knowledge components are dense in some clusters, whereas they are nonexistent between other clusters. In almost decomposable knowledge bases (Simon, 1962), some knowledge components are more densely connected with each other than they are with other components, but, simultaneously, some ties relate denser areas with each other (Yayavaram & Ahuja, 2008). Finally, in a non-decomposable structure, each knowledge component is strongly tied to each other component, such that no set of nodes can be characterized as a cluster because of the thickness of links between ensembles of components (Yayavaram & Ahuja, 2008).

We discriminate between two kinds of innovation: modular and architectural innovation. Henderson and Clark (1990, p. 12) define architectural innovation as innovation in which the central notions are “reinforced” but the relationships between the central parts are altered. They see modular innovation as the opposite, as it changes the central components but leaves the relationships unaltered.

The empirical context of the LIB industry represents the early phase of the industry’s life cycle, given that not many exit events have occurred since its emergence in 1991. Since the LIB industry is technology-intensive, these phases are characterized by a lack of industry-specific knowledge (Gort & Klepper, 1982), by several rivaling technologies, and by the absence of a dominant design (see also Kapoor & Furr, 2015; Suarez & Utterback, 1995). Moreover, there is severe competition among the distinctive technologies of LIBs. Taken together, modular and architecture innovations are particularly significant in this context, compared to their lesser significance in the more mature phases of an industry’s life cycle.

2.1 The linear effect of decomposability on modular innovation

Prior research suggests that innovation often emerges from the interplay between specialized and broad knowledge and from the integrative mechanisms that connect the two (Katila & Ahuja, 2002; March, 1991; Yayavaram & Ahuja, 2008). Specific knowledge fosters a thorough expertise in a particular domain and involves the recurring application of a few elements (Katila & Ahuja, 2002). In contrast, broad knowledge enables firms to be exposed to divergent ideas and applications, as well as novel arrangements of existing ones (Katila & Ahuja, 2002; March, 1991).

Compared to other types of firm innovation, however, modular innovation is more effective when combined with specialized knowledge. To acquire such knowledge, firms need to test possible combinations to explore areas in which new combinations can be beneficial (Carnabuci & Operti, 2013). With the repeated use of existing ties, a company can delve deeper into its knowledge (Argyres & Silverman, 2004; Carnabuci & Operti, 2013; Katila & Ahuja, 2002). The acquisition of deep specialized knowledge in one specific domain can be realized most fully through a decomposable knowledge structure, as such firms are capable of systematically refining existing knowledge combinations to tackle challenges and explore new use-cases, thus achieving localized innovation within specific knowledge clusters (Carnabuci & Operti, 2013).

Meanwhile, modular innovation requires less broad knowledge, which can be acquired by searching for distinctive new combinations outside existing sets of local knowledge. For example, both cathodes and anodes are major components to run LIB cells, and technological advancement in both components significantly improves the overall performance of LIB cells. However, to develop more technologically advanced cathodes, a firm would not have to consider potential combinations with knowledge clusters related to the anode. Rather, considering combinations within cathode knowledge clusters is sufficient to produce a more advanced cathode. Further, because the degree of recombination with other disconnected knowledge elements is lower, modular innovation also requires less of an integration mechanism to link newly identified knowledge components across clusters.

Although a high level of decomposability lacks integration mechanisms to link various knowledge across clusters, it does not limit the likelihood of combination within existing clusters. Rather, there is an adverse effect of low decomposability on modular innovation. In less decomposable knowledge bases, when firms evaluate any change in a knowledge component, they must also consider the effect of the alteration of all the other associated components (Yayavaram & Ahuja, 2008). Such a high degree of interdependency complicates the search procedure and reduces the effectiveness of a local search (Yayavaram & Ahuja, 2008). At the same time, standardized interfaces between components enable research and development to be delegated to dedicated teams, leading to more efficient innovation procedures and localized and decomposable knowledge aggregation (Ulrich, 1995). Taken together, any integration mechanisms between groups of nodes relate the search in one, at least to a certain degree, to the same process in another (Yayavaram & Ahuja, 2008). However, in a decomposable knowledge base where this integration function is absent (Yayavaram & Ahuja, 2008), the coupling may be less of a barrier, since improvements in a local knowledge cluster may be sufficient to develop specialized knowledge, leading to modular innovation.

Thus:

Hypothesis 1: The increasing decomposability of a firm's knowledge structure is be positively associated with modular product innovation.

This also resembles previous research on the "mirroring hypothesis" and its transfer to studies of vertical integration (Argyres & Bigelow, 2010, p. 843; Henderson & Clark, 1990).

2.2 The curvilinear effect of decomposability on architectural innovation

A company that aims to be effective in delivering new product linkages needs to adopt a focused system as well as breadth and depth in technological problem solving (Henderson & Clark, 1990; Magnusson et al., 2003). In other words, a firm's architectural innovation hinges both on the development of sophisticated processes for technology combination and on the possession of a broad and deep know-how, all of which allow the firm to render combinations of knowledge components that often cut across knowledge domains (Magnusson et al., 2003).

These three mechanisms – exposure to new ideas, deep understanding of a specific knowledge domain, and integration – can be realized more effectively with nearly decomposable knowledge bases compared to those with extremely low or high levels of decomposability. Meanwhile, although an extremely high level of decomposability is advantageous for generating deep specialized knowledge, it provides no integration mechanisms to link specialized knowledge across the clusters within a firm's knowledge base (Yayavaram & Ahuja, 2008). More importantly, without integration between clusters in highly decomposable knowledge bases, any changes in one knowledge cluster cannot be detected by individuals involved in other clusters. As a result, although a novel technology established in one cluster may have a positive link with another, there will be no knowledge exchange between two distant clusters in networks with an extremely high level of decomposability (Yayavaram & Ahuja, 2008). Modularity has also been associated with obstacles to architectural innovation (Henderson & Clark, 1990; Ulrich, 1995).

Given that specialization needs to be accompanied by integration in order to achieve architectural innovation (Henderson & Clark, 1990), intermediate degrees of decomposability can compensate for these shortcomings (Yayavaram & Ahuja, 2008). Intermediate levels consequently enable an improved exploration of new knowledge and offer integrative mechanisms to relate the previously unfamiliar concepts revealed through this wide-ranging exploration with specialized knowledge, thus making effective combinations possible (Yayavaram & Ahuja, 2008).

Thus:

Hypothesis 2: The increasing decomposability of a firm's knowledge structure has an inverted U-shaped relationship with architectural product innovation.

3. Data and methodology

3.1 Industry setting and construct validity

We carry out our analysis in the empirical context of the global Lithium-Ion Battery (LIB) industry from 1991 to 2013. The LIB cell manufacturing industry initially emerged in 1991 with the development of the first commercial LIB by Sony Corporation.

Insert Figure 1 about here.

Figure 1 depicts the pattern of entry into the LIB industry. The number of entrants rapidly increased from around 1999 to a peak in 2009, then declined gradually due to strong competition, the global financial crisis, and weakening governmental support (see also Kapoor & Furr, 2015). However, the observed entry pattern shows that the industry has not yet experienced a major shake-out, with few exit events occurring during the studied period. Moreover, since there are multiple competing technologies and no dominant design yet (Suarez & Utterback, 1995), the current state of the industry represents the early stage of an industry life cycle (Wagner et al., 2013).

The LIB cell manufacturing industry represents a nearly perfect setting for this study for several reasons. First, the knowledge creation processes within this industry are particularly intricate (Stephan, Schmidt, Bening, & Hoffmann, 2017). Second, the high research and development

(R&D) intensity of the LIB industry implies that the industry is characterized by constant technological change (Wagner et al., 2013) and that most LIB firms routinely patent their inventions. This context is well suited for a study of the role of a company's knowledge base structure on its innovativeness. Third, in the early stage in the industry life cycle (Mueller, Sandner, & Welpe, 2015; Wagner et al., 2013) both modular and architecture innovations are pervasive, as firms must actively develop knowledge about components as well as knowledge of how these components can be integrated (Henderson & Clark, 1990). This allowed us to easily observe the two types of product innovation – modular and architectural. While much of the modularity theory has been developed based on hardware, Ulrich (1994, p. 220) noted that the ideas should also be transferable to "chemical products."

An LIB cell consists of four components: a cathode, an anode, a separator, and an electrolyte. A clear, bijective relationship between functions and components is one of the core parts of Ulrich's (1995) modularity definition (Baldwin & Clark, 2000). Cathodes, for example, release and accept ions during charging and discharging. Cathode materials can be optimized independently of the other battery components. For instance, numerous cathode materials can be combined with electrolytes based on Lithium hexafluorophosphate ($LiPF_6$) in alkyl carbonates (Goodenough & Kim, 2009; Martha et al., 2009). Within LIB cell research, strong efforts are undertaken to develop more advanced cathodes, as firms' technological choices in cathodes differentiate LIB cell performance in terms of power, density, and life cycle by providing higher potentials and larger specific charges (Battery University, 2017b). For example, Sony initially produced LIB cells with Lithium Cobalt Oxide (LCO) as a cathode (Battery University, 2017a); later, it developed the Lithium Iron Phosphate (LFP) cathode to enhance the overall performance of its LIB cells in terms of power, density, and life cycle (Sony, 2009). It is important to note that using an advanced cathode in an LIB cell does not necessarily require changes in the cell architecture itself. For example, the change from LCO to LFP cathodes will not necessarily require a change in LIB cell design from cylindrical to prismatic. In other words, newly developed LFP cathodes can be applied to existing cylinder LIB cell designs in order to create better-performing cells. Moreover, firms develop new cathodes to enter into promising markets with high consumer demand. For example, to enter the electric vehicle market, firms may feel urged to develop more advanced cathodes such as nickel manganese cobalt oxide (NMC) cathodes. With less advanced cathodes such as LCO, firms may only be competitive in the more or less stable consumer electronic market. If firms would like to expand their market scope from one to the other, developing a more advanced NMC cathode can be beneficial.

Given that modular innovation is defined as improving product innovativeness by changing key components within products that do not significantly affect the product architecture (Henderson & Clark, 1990), its key feature is that it permits companies to build related products grounded in the same design, thus helping to satisfy a variety of markets (Argyres & Bigelow, 2010). Consequently, cells share the same advantage with other modular designs – that is, a large variety of possible configurations. In accordance with this notion, previous studies have also referred to the different lithium-ion cell chemistry combinations as “permutations” (Thielmann, Isenmann, & Wietschel, 2010, p. 14) of the possible configuration choices. Therefore, technological advances in cathode components have a high level of construct validity with the concept of modular innovation.

In addition to the modularity, the architectural aspects of the LIB industry have also attracted the attention of innovation scholars (Stephan et al., 2017). Indeed, the cell architecture has a significant influence on the product performance. The most prominent cell designs are cylindrical, button, prismatic, and pouch geometries. The differences in cell architecture lead to variations in performance in terms of energy density, energy efficiency, and duration. For example, while the cylinder-shaped design has good cycling specifications and can endure a long calendar life, this design has a low packaging density, leading to an inefficient use of space (Battery University, 2017c). In contrast, the prismatic cell design is space-efficient but has a shorter life cycle than the cylindrical design (Battery University, 2017c). By using a laminated architecture, the pouch cell design uses conductive foil tabs, which are connected to the electrodes and reach to the outside in a completely sealed arrangement, thus making the most efficient use of space (Battery University, 2017c). The cell architecture also has important implications for product safety. Depending on the architecture, manufacturing deviations can lead to a higher risk of ‘thermal runaways’ (Finegan et al., 2015) and thus reduce safety, which is a crucial product differentiator. The different product properties lead to different favorite architectures among customers. This also holds true for important applications such as electric mobility; for example, while Tesla is using cylindrical cells, BMW prefers prismatic cells, and Jaguar is developing a car based on pouch cells (Becker, 2017). In sum, as the performance of LIB cells is partly determined by the choices of cell design, the number of cell designs that a company is able to develop has a high level of construct validity with the concept of architecture innovation.

3.2 Data

The data-gathering process of the independent variable – that is, the level of decomposability in each sample company’s knowledge base – began by counting the total number of around 268 LIB firms listed in the battery database of Shmuel De Lion Energy, Ltd., to which we subscribe. Second, we searched through Espacenet, Google Patents, Orbis, and firms’ websites to identify the firms with patents. Third, we used *Who Owns Whom* corporate directories to obtain information on the ownership structure of LIB firms. After identifying the approximately 225 LIB firms with patents, we used PATSTAT to retrieve their patents. The advantage of PATSTAT compared to USPTO is that it gathers data from all major patent offices, including USPTO, European Patent Office (EPO), Japan Patent Office (JPO), State Intellectual Patent Office (SIPO), and Korea Patent Office (KPO).

Although patents are frequently used as metrics of various types of firm innovative outputs (Griliches, 1998; Guan & Liu, 2016), challenges in using patent-based measures remain. Patent values are often highly skewed, and patents cannot capture the innovativeness of a commercialized product sold to users (Gambardella, Harhoff, & Verspagen, 2008; Gittelman, 2008; MingJi & Ping, 2014), since the benefit that can be reaped from a patent is governed by several influences beyond its technological usefulness (e.g., whether the company can commercialize and appropriate the invention; (Teece, 2006; Yayavaram & Ahuja, 2008). More importantly, on a conceptual level, a patent represents the fundamental knowledge through which new products have been developed, rather than newly commercialized products themselves. To overcome such challenges on the dependent variable side, we decided to collect detailed information on over 18,000 LIB cell products through LIB cell technological specification documents from Shmuel de Lion Energy, Lexis-Nexis Academic press announcements, and firm websites to generate our dependent variables. We ran multiple steps to collect information on cathode materials, cell shapes, and the launch year of each LIB cell. First, we conducted a keyword-based search including the names of five types of cathodes, the names of four types of cell shape, and any four-digit number from the full text of each file through our designed algorithm. As the majority of information on cathodes and cell types was not extracted through this algorithm, and most four-digit numbers extracted did not represent information on the launch year of LIB cells, our next step was to manually check in each PDF file about a LIB cell’s cathode materials and cell shapes, whether its launch each year could be found. Since a good portion of the sample firms have developed multiple LIB cells with a combination of one particular cathode (i.e., LCO) and cell shape (i.e., cylinder) during one particular year, the total number of observations shrank accordingly.

Finally, we collected data from VentureXpert, the Department of Energy, local newspapers, and industry trade journals to control for the firm- and environmental-level variances. After merging the data set including independent, dependent, and control variables, the final sample included 67 global LIB cell-manufacturing firms and 587 observations, which we then used to examine the distinctive effect of a company's knowledge structure on its type of innovation during the sample period.

3.3 Measures

Dependent Variables

In this study, two dependent variables – modular and architectural innovations – were developed based on detailed LIB cell data. As noted earlier, cathode material represents a core knowledge component of LIB cells, as further advances in cathode materials are essential for battery performance enhancement, which allows firms to consider entering promising markets (e.g., electric vehicle and stationary energy storage). The first dependent variable, **Modular Innovation$_t$**, is a yearly count variable capturing the accumulated number of choices on cathode materials since a firm's founding in year t. The five most commonly used cathode materials are LCO, spinel, NMC, olivine, and NCA. In contrast, cell shapes determine how all components in LIB cells are integrated and interact. The second dependent variable, **Architecture Innovation$_t$**, is a yearly count variable capturing the accumulated number of firms' choices on cell shapes from their founding in year t. The four most commonly used cell shapes are cylinder, button, prismatic, and pouch.

Empirically, we used detailed Lithium-Ion Battery cell data to generate information on these two types of product innovation. As cathode materials represent a core knowledge component of LIB cells, we examined modular innovation based on the number of cathode materials developed by firms. In contrast, as cell shapes describe the way knowledge components are interrelated, we investigated architectural innovation based on the types of cell shapes developed by firms.

Independent Variable

We followed prior research (e.g., Yayavaram & Ahuja, 2008; Yayavaram & Chen, 2015) to generate a measure of **decomposability**. To do so, multiple steps were required. First, we began by creating a company's knowledge base. A company's knowledge base at *t* is presumed to be given by all the patents that the company has obtained during the preceding three years (i.e., from *t – 3* to *t –1*). Following Fleming and Sorenson (2001) (as cited in Yayavaram & Ahuja, 2008) , we also used the technology classes in which patents are filed as a proxy for the nodes in a company's knowledge base. A tie between two nodes is formed when a patent is developed by using these two nodes.

To minimize the influence of right censoring, we ended the study period in 2013 to allow sufficient time for the approval of patent applications that sample firms submitted during the sample period. We used Cooperative Patent Classification (CPC) to create the sample firms' knowledge bases. Compared to the International Patent Classification (IPC), the CPC has been introduced rather recently and allows for technological resolution with unprecedented clarity (Mueller et al., 2015).

To identify LIB-related patent classes, we started by looking at all the classes that were assigned to all the patents of the companies in our selection. Next, we ranked the CPC by the number of patents to which they were assigned and, in the process of generating the knowledge networks, considered only the top 100. In determining the ranking, we excluded the patents assigned to several large companies in our sample, including Panasonic, Sony, and Samsung, due to their high level of patent activity across various industries not related to LIBs. For the next step, we used the previously determined 100 CPC classes to generate a company's knowledge base in year *t*, which comprises patents from the three previous years. Similar to previous research (Yayavaram & Chen, 2015), we chose three-year averaging to reduce the influence of annual variations in patenting.

To characterize the firms' knowledge network structure, we relied on the *level of decomposability*, which is derived from the clustering coefficient (Albert & Barabási, 2002; Watts & Strogatz, 1998; Yayavaram & Ahuja, 2008). The value ranges from 0 to 1, where 0 represents fully decomposable knowledge bases, and 1 represents fully integrated knowledge bases. For calculation, we used a code kindly provided by Yayavaram and Ahuja (2008).

Control variables

To reduce the likelihood of alternative interpretations, we accounted for several firm- and environment-level variables that might be veiling the effect of the variables of interest. We controlled for organizational-level factors with measures of **Firm Patent Stock**, **Firm Technological Diversity**, **Firm Size**, **Firm Age**, and **Integrator**.

Firm Patent Stock: A firm with large patent stocks tends to have deep technological resources and absorptive capacity (Silverman, 1999). The firm can explore more combinations and may thus be more effective when searching (Kogut & Zander, 1992; Yayavaram & Chen, 2015), eventually leading to more innovation (Silverman, 1999). We controlled for the number of patents awarded to firm *i* in the past three years (Ahuja & Katila, 2001; Yayavaram & Ahuja, 2008).

Firm Technological Diversity: Prior literature posits that the manner in which firms develop their technological knowledge significantly affects the degree of firm innovation (Garcia-Vega, 2006; Miller & Arikan, 2004). A firm's technological diversity represents the extent to which firms draw intensively from specific technological areas, measured using the Herfindahl index (Blau, 1977). We calculated the index using the following formula:

$$D=1-\sum p^2_{itk}$$

where P_{itk} stands for the share of company *i*'s patents in the technology classification *k* within the averaging window. A three-year moving window may represent an LIB company's search behavior more accurately because companies in the sample are those that receive few, if any, patents per year (Rothaermel & Deeds, 2004). The minimum value of 0 represents the exclusive usage of one specific technological area in developing new products, whereas values close to 1 quantify a state in which (nearly) all patents held by a focal firm have been assigned to a different class (Schildt, Keil, & Maula, 2012). For example, a value of 0.05 indicates a low technological diversity, whereas a value of 0.95 corresponds to a high level of technological diversity. As a robustness check, we calculated another measure of technological diversity during the past five years.

Firm Age: We also included firm age in the models for two reasons. First, as firms grow older, they may use their obtained knowledge rather than search for new technologies, leading to reduced firm innovativeness (Sørensen & Stuart, 2000). Second, earlier studies have demonstrated that models of size effects that do not control for age result in skewed approximations of the effects of size on organizational outcomes (Barron, West, & Hannan, 1994: cited in Sørensen & Stuart, 2000). *Firm Age* was calculated as a given year *t* minus the founding year of the company and used after applying the logarithm.

Firm Size: Prior literature suggests that larger companies are less likely to be resource constrained and, thus, more likely to pursue innovation (Agarwal & Audretsch, 2001; Teece, 1992). We measured the size of the company by the total number of employees. A company's size is frequently quantified in terms of revenues or market share, but many firms in the sample used in this study are privately held companies and therefore do not publish this information. Consequently, quantifying the size of a company through the size of the workforce is a useful substitute (Rothaermel & Deeds, 2004; Shan, Walker, & Kogut, 1994). *Firm Size* was calculated as the total number of employees, including executives. This measure was also used in a log transformation.

Integrator: Prior literature maintains that companies that are vertically integrated may not benefit from economies of scale and may have to handle more complex processes (Randall & Ulrich, 2001, as cited in Dowell, 2006), thus affecting search scope. We controlled for *Integrator* by using a dummy, which assumes the value of 1 if the company not only produces cells but also packs and assembles cells into batteries, whereas it assumes a value of 0 if the firm only focuses on cell manufacturing activity. We gathered evidence on boundary choices at founding from firms' websites and industry publications. We also ensured that these boundary choices remained unchanged within the sample firms (Qian, Agarwal, & Hoetker, 2012).

As firms develop more advanced components to enter into promising markets within the LIB industry, there is a high level of correlation between the number of firms' market scope and types of cathode components. *Market Scope*$_{t\text{-}1}$ is a count variable capturing the accumulated number of LIB firms' product market application from their founding within the LIB industry in year t-1. From industry trade journals, ten distinct product market application sectors were identified: (1) consumer electronics, (2) military, (3) medical, (4) aerospace, (5) marine, (6) industrial, (7) UPS (Uninterruptible Power Supply), (8) RFID (Radio-Frequency Identification), (9) automotive, and (10) energy storage. We collected yearly information on market scope since founding from industry trade journals (i.e., BatteryPowerOnline), and LIB cell technological specification documents from Shmuel de Lion, Lexis-Nexis Academic press announcements, and firm websites. We also controlled for the number of cathodes from the prior year by generating a one-year time lagged variable (**Modular Innovation**$_{t\text{-}1}$) and for the number of cell shapes from the prior year by generating a one-year time lagged variable (**Architecture Innovation**$_{t\text{-}1}$).

At the environmental level, we controlled for possible time period effects due to changes in policies and regulations related to the LIB industry using **Year Dummy** variables regarding the different years in which the companies operated. The omitted category was 1991 – the first year of the study period. These variables allowed us to control for factors specific to a particular year that might affect firms' product innovation for that year. Lastly, since national economic situations and culture may affect the pace and types of firms' new product development, we controlled for the country in which the firm was founded by creating a dummy variable (**US**), which we coded as 1 if the company's headquarters are located in the United States and 0 otherwise.

3.4 Model specification and estimation

Our data structure uses yearly panel data, which is unbalanced, implying that the number of observations per company differs, since some companies exit the panel before others (e.g., Dencker & Gruber, 2015). The unit of analysis is the firm-year. Either firm-fixed or random effects can be employed to account for unobserved firm heterogeneity (Greene 1997, as cited in Phelps, 2010), including differences in motivations to pursue and abilities to develop new products. However, as random effects models rely on the assumption that there is no correlation between errors and regressors, we verified the suitability of the random effects model by conducting a Hausman (1978) test. We also checked for first-order serial autocorrelation in the errors. A random effects model is appropriate, since Hausman specification tests were not significant, and significant serial correlation was not present.

The dependent variables – the number of cathode materials and cell shapes that the sample firms developed over time – take on only non-integer values. As an over-dispersion problem was not detected, we use a Poisson regression model for our study. We also utilized robust standard errors to account for possible non-independence across observations (Dencker & Gruber, 2015).

4. Results

Table 1 reports a descriptive statistics and correlation matrix for the variables analyzed in our analyses. Our models do not suffer from multicollinearity issues, as the highest variance inflation factor (VIF) among the variables is 3.06 (*Firm Tech Diversity),* which is below the recommended cutoff level of 10 (Lee & Berente, 2013; Neter, Kutner, Nachtsheim, & Wasserman, 1996). For all models, Huber-White robust standard errors are given.

Insert Table 1 about here.

Table 2 presents the results of the panel Poisson regression analysis to test Hypothesis 1. Hypothesis 1 predicts a positive effect of the level of decomposability within a firm's knowledge network on modular innovation. Model 3 contains control variables only, and model 4 adds the level of decomposability. Although there are five commonly used cathode materials – LCO, spinel, NMC, olivine, and NCA – each cathode's invention year is significantly different. For example, while LCO was invented in 1980, NMC, the newest cathode material, was invented in 1999. This means that all five cathodes were not available until 1999. Given the difference before and after 1999, we restricted the observation of cathode development after 1999 to control for this crucial difference in market environments. After excluding events before 1999, the total number of observations was reduced to 502. As a robustness check, in Model 1 we included control variables only, while Model 2 adds the level of decomposability to Model 1. The positive coefficient of the level of decomposability in both Model 2 ($p<0.05$) and Model 4 ($p<0.05$) implies that modular innovation is realized with the high level of decomposability, supporting Hypothesis 1. For clarity, with the high level of decomposability, the value tends toward 1, whereas with the low level of decomposability, the value tends toward 0.

Insert Table 2 about here.

Table 3 presents the results of the panel Poisson regression analysis to test Hypothesis 2. Hypothesis 2 predicts a curvilinear effect of the level of knowledge network decomposability on architecture innovation. Model 4 contains control variables only. Model 5 adds the level of decomposability, and Model 6 adds the square term. Again, to control for the crucial difference in market environments, we restricted the observations of firms' development of cell design after 1999. In Model 1, we included control variables only. Models 2 and 3 add the level of decomposability and the square term to Model 1, respectively. Both Models 3 and 6 provide strong support for Hypothesis 2 ($p<0.05$; $p<0.05$), indicating that the increasing decomposability of a firm's knowledge structure has an inverted U-shaped relationship with architectural product innovation. We also tested for additional criteria, as recently suggested by Haans, Pieters, and He (2016), to ensure that an inverted U-shaped curve could indeed be concluded.

Insert Table 3 about here.

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5. Discussion

Our study responds to two important calls highlighting that 1) the structural aspect of a firm's knowledge base itself needs to be fully understood as a key driver for firm innovation

(Yayavaram & Ahuja, 2008) and 2) the innovation literature will be advanced by examining the various types of product innovation beyond simple categories of incremental and radical innovation (Guan & Liu, 2016). By distinguishing between different kinds of firm innovation, our paper indicates that the structural features of a company’s knowledge base can differentially affect the new product development processes depending on the type of innovation. More specifically, for modular innovation, a more decomposable knowledge structure is always beneficial, whereas for architectural innovation, nearly decomposable knowledge structures are better than either decomposable or integrated ones. This study thus provides further understanding of how and why the structural conditions of a focal company’s knowledge base influence the type of product innovation.

5.1 Contributions and implications

This study contributes to a burgeoning literature investigating how the different types of structural patterns of its knowledge base affect overall firm innovativeness (Guan & Liu, 2016; Wang et al., 2014) by distinguishing between different kinds of firm innovation. The study shows that, depending on the type of firm innovation, the same structural pattern of a company’s knowledge base may have distinctive performance implications.

Understanding the level of decomposability in a company’s knowledge base will advance the literature on product architecture (Baldwin & Clark, 2000; Ethiraj & Levinthal, 2004; Sanchez, 1996; Schilling, 2000) by showing that a firm’s innovativeness, in terms of modular and architectural innovation, can be predicted by the way the firm’s knowledge components are structurally interacted. This not only confirms that a company’s knowledge base structure reflects the inner formation of the product it is designing (Henderson & Clark, 1990; Yayavaram & Ahuja, 2008) but also demonstrates that the linkage between a firm’s knowledge structure and its product architecture reflects the types of innovation a firm decides to follow.

Furthermore, our study supplements the social network literature showing how the network structure influences different types of firm innovation. Our findings call to also extend research on the influence of social networks on different types of innovation.

5.2 Limitations and future research

We are cognizant of the shortcomings of the present study. First, our study is restricted to just one high-tech area, the LIB industry, which is characterized by several rivaling technologies and the absence of a dominant design (see also Kapoor & Furr, 2015; Suarez & Utterback, 1995). Considering other industrial contexts would thus be an interesting avenue for future research.

Given that innovation activities are embedded into multiple networks including collaboration and knowledge networks within a firm, another promising future direction is to examine 1) the influence of each network and 2) the joint effect of the two on firm innovation as a whole, as well as on different kinds of innovation. Previous research (e.g., Brennecke & Rank, 2017; Wang et al., 2014) regarding the coupling of these networks has mostly looked at individual firms. Studying both knowledge and social networks across multiple firms would lead to additional valuable insights.

It would also be interesting to further explore how the findings can be employed to optimize firms' knowledge bases with respect to the different types of innovations, for example by creating new links within the organization (e.g., through *structural recombination*; (Karim & Kaul, 2015) or by introducing new knowledge clusters via targeted acquisitions.

Furthermore, although both hypotheses are supported, it should be noted that the number of observations shrank drastically after merging knowledge network data and LIB product data. As an extension, a future study could include two other major battery technologies – lead-acid and nickel-based – by collecting patents and product data. As all three technologies are based on a similar architecture (Battke, Schmidt, Stollenwerk, & Hoffmann, 2016), the rechargeable battery industry is an ideal place to examine the impact of the knowledge structure in the development paths of new battery products.

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7. Tables and figures

Table 1. Descriptive statistics and correlation matrix

Variable	Mean	Std. Dev.	Min.	Max.	1	2	3	4	5	6	7	8	9
1. No of celltypes	0.62	0.91	0	4.00									
2. No of cathode materials	0.71	1.02	0	5.00	0.83*								
3. Level of decomposability	0.31	0.35	0	1.00	-0.04	-0.09*							
4. No of patents (3 yr)	287.21	816.12	1	7422.00	-0.13*	-0.12*	-0.06*						
5. Tech diversity (5 yr)	0.75	0.30	0	0.98	0.01	0.06	-0.80*	0.22*					
6. Ln firm age	2.65	1.02	0.69	4.93	-0.01	-0.02	0.01	0.22*	0.08*				
7. Ln No of employees	6.61	2.93	1.95	12.70	-0.31*	-0.33*	0.12*	0.26*	-0.03	0.57*			
8. Integrator	0.72	0.45	0	1.00	0.04*	0.10*	-0.10*	0.19*	0.11*	0.21*	0.44*		
9. US	0.26	0.44	0	1.00	0.13*	0.13*	-0.22*	-0.12*	0.23*	-0.03	-0.38*	0.03	
10. No of market scopes (t-1)	0.73	1.09	0	5.00	0.76*	0.76*	-0.10*	-0.13*	0.05	-0.02	-0.33*	0.09*	0.17*

* $p<.05$

Table 2. Results of random-effects panel Poisson regression analysis predicting firm modular innovation

Variable	**Model 1** (yr>1998)	**Model 2** (yr>1998)	**Model 3**	**Model 4**
Level of decomposability		0.491 (1.99)**		0.497 (2.01)**
No of patents /thsd. (3 yr)	-0.140 (0.72)	-0.178 (0.93)	-0.122 (0.62)	-0.160 (0.82)
Tech diversity (5 yr)	0.274 (1.14)	0.780 (2.40)**	0.265 (1.09)	0.777 (2.40)**
Ln firm age	-0.379 (3.04)***	-0.374 (2.98)***	-0.386 (3.08)***	-0.382 (3.03)***
Ln No of employees	-0.024 (0.43)	-0.035 (0.65)	-0.026 (0.47)	-0.038 (0.68)
Integrator	-0.120 (0.80)	-0.079 (0.54)	-0.117 (0.78)	-0.076 (0.52)
US	-0.017 (0.15)	-0.031 (0.29)	-0.009 (0.08)	-0.022 (0.20)
No of cathodes$_{t-1}$	0.779 (7.99)***	0.772 (8.24)***	0.779 (8.05)***	0.772 (8.30)***
No of market scopes$_{t-1}$	0.154 (2.07)**	0.158 (2.20)**	0.154 (2.07)**	0.158 (2.21)**
Year dummies	Included	Included	Included	Included

Constant	-0.552	-1.017	-0.523	-0.994
	(1.56)	(2.74)***	(1.45)	(2.68)***
lnsig2u	-3.539	-3.994	-3.481	-3.903
	(2.93)***	(2.18)**	(3.08)***	(2.38)**
N	502	502	587	587

* $p<0.1$; ** $p<0.05$; *** $p<0.01$

Table 3. Results of random-effects panel Poisson regression analysis predicting firm architecture innovation

Variable	Model 1 (yr>1998)	Model 2 (yr>1998)	Model 3 (yr>1998)	Model 4	Model 5	Model 6
Level of decomposability		0.033	1.726		0.045	1.760
		(0.14)	(2.24)**		(0.19)	(2.28)**
Level of decomposability^2			-1.747			-1.770
			(2.53)**			(2.56)**
No of patents /thsd. (3 yr)	-0.272	-0.275	-0.446	-0.246	-0.250	-0.417
	(1.31)	(1.33)	(1.84)*	(1.18)	(1.21)	(1.73)*
Tech diversity (5yr)	0.565	0.595	0.298	0.556	0.599	0.295
	(3.08)***	(2.23)**	(1.11)	(3.02)***	(2.23)**	(1.10)
Ln firm age	-0.335	-0.334	-0.339	-0.341	-0.340	-0.345
	(2.94)***	(2.93)***	(2.91)***	(3.00)***	(2.99)***	(2.97)***
Ln No of employees	-0.049	-0.050	-0.048	-0.050	-0.052	-0.050
	(1.27)	(1.11)	(1.10)	(1.29)	(1.14)	(1.13)
Integrator	0.029	0.032	0.033	0.030	0.034	0.035
	(0.33)	(0.35)	(0.34)	(0.34)	(0.37)	(0.36)
No of cell types$_{t-1}$	0.799	0.799	0.778	0.801	0.800	0.780
	(15.21)***	(15.43)***	(14.23)***	(15.08)***	(15.29)***	(14.12)***
No of market scopes$_{t-1}$	0.188	0.188	0.191	0.188	0.188	0.191
	(3.80)***	(3.79)***	(3.78)***	(3.80)***	(3.80)***	(3.78)***
US	0.099	0.098	0.112	0.111	0.110	0.124

	(1.02)	(1.02)	(1.15)	(1.09)	(1.08)	(1.21)
Year dummies	Included	Included	Included	Included	Included	Included
Constant	-0.895	-0.920	-0.810	-0.878	-0.912	-0.798
	(2.29)**	(2.47)**	(2.28)**	(2.26)**	(2.46)**	(2.26)**
lnsig2u	-15.286	-15.293	-15.511	-14.312	-14.322	-15.438
	502	502	502	587	587	587

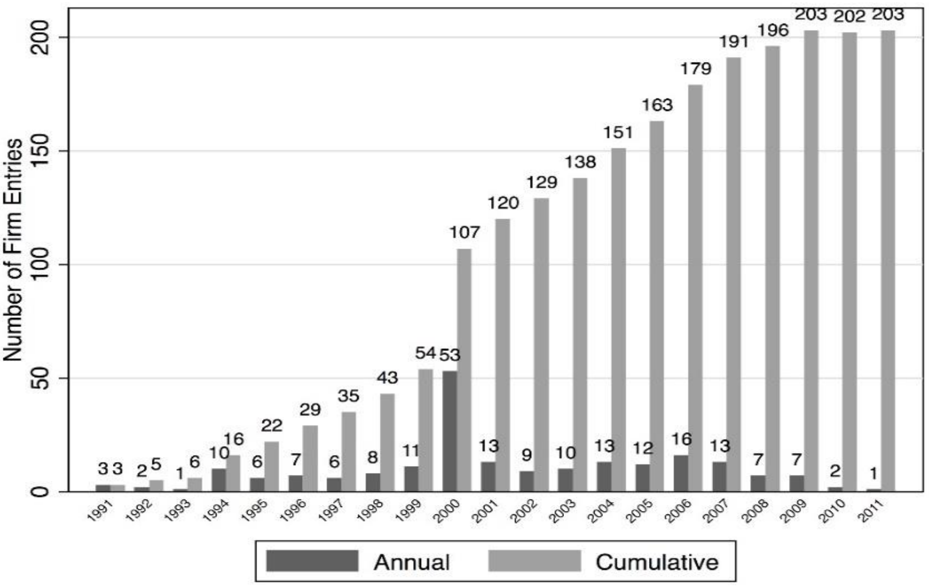

Figure 1. Entrants per year and total no. of firms per year in the global LIB industry

2.3. Essay 3 – Sharing electricity storage at the community level: An empirical analysis of potential business models and barriers

Full reference:

Müller, S. C., & Welpe, I. M. (2018). Sharing electricity storage at the community level: An empirical analysis of potential business models and barriers. *Energy Policy*, 118, 492-503.

Abstract:

More and more households are installing residential electricity storage systems to increase the self-consumption of electricity they produced. Some governments have accelerated this development through specific financial support schemes to offset the costs, which still remain high. Compared to the use of single-household systems, the sharing of mid-scale electricity storage systems in neighborhoods could reduce the Levelized Costs of Storage (LCOS). However, a model for the shared usage of storage by multiple households has yet to emerge. We investigated eight demonstration projects in Germany and Western Australia with capacities between 100 and 1100 kWh with respect to potential business models and barriers in a cross-case study based on document analyses and expert interviews. We found that models relying on the transmission of electricity from individual rooftop photovoltaics to a shared storage system through the public grid are facing significant regulatory barriers. Removing these policy barriers would enable a more efficient use of electricity storage systems. By contrast, projects relying on a less regulated microgrid managed by the administration or strata entities of multi-household developments already seem promising under the current regulatory framework.

Author contributions:

S.C.M. is the first author of the paper; I.M.W. is a contributing author. S.C.M. developed the research question and design, supervised by I.M.W. S.C.M. carried out the data collection, expert interviews, coding, and analysis. S.C.M. wrote the manuscript, receiving suggestions and feedback from I.M.W. S.C.M. carried out the submission process and correspondence.

Sharing electricity storage at the community level:

An empirical analysis of potential business models and barriers

1. Emergence and integration of electricity storage systems

The strong global momentum towards renewable energy will, in all likelihood, increase the important role of photovoltaics (PV) and wind power (Obama, 2017). With increasing shares, however, the intermittency of renewable energies will become progressively problematic. The impact of fluctuating power generation on electricity systems as a whole is increasingly recognized on an international level (International Energy Agency, 2014). Backup capacities such as grid extension or storage can help to meet load requirements for high shares of intermittent renewable energy (Steinke et al., 2013). Electricity storage is an important technology option if further cost degressions can be achieved (Braff et al., 2016). While it has been debated whether there is a need for electricity storage in the short term (Fürstenwerth and Waldmann, 2014; Schill, 2014), battery storage coupled to residential PV, in particular, is gaining considerable traction and is therefore likely to play a significant role in the transition (Agnew & Dargusch, 2015). Recent studies on patent applications in electrochemical electricity storage technologies support this reasoning (Golembiewski et al., 2015; Mueller et al., 2015). Many private and public laboratories undertake significant efforts to optimize battery chemistries (e.g., Larcher and Tarascon, 2015; Lin et al., 2017), as well as battery (e.g., Campestrini et al., 2016; Hannan et al., 2017) and energy (e.g., Olatomiwa et al., 2016; Thien et al., 2017) management systems. These advances are also supported by demand from the electric vehicle industry, where module costs have come down significantly in recent years (Nykvist and Nilsson, 2015). Further cost reductions are expected due to learning effects and economies of scale (Kittner et al., 2017; Schmidt et al., 2017). Technological progress gives policymakers choices regarding type, distribution, and support of electricity storage systems. To avoid the lock-in to suboptimal solutions, however, an early and careful studying of policy design is required.

Indeed, Fares and Webber (2017) showed that residential storage, a currently evolving market segment, can lead to overall increased emissions due to inefficiencies. At the same time, studies show that a combination of multiple applications (He et al., 2011; Lombardi and Schwabe, 2017; Stephan et al., 2016) or the sharing of systems by multiple users (Parra et al., 2015; Parra et al., 2017) would increase the (cost) effectiveness of electricity storage systems. To date, there is only little insight how the sharing between users or applications could be combined to business models and what barriers pilot projects in this area are facing. We sought to fill this gap by conducting a cross-case study on current demonstration projects in Germany and Western Australia.

The remainder of this paper is organized as follows: The following section reviews the essential theoretical background. Section 3 describes materials and methods. Section 4 gives a brief overview of the cases. Section 5 presents the results of the cross-case analysis, i.e., key design possibilities, barriers and exemplary models. Finally, Section 6 gives conclusions and discusses the policy implications of our findings.

2. Theoretical background

2.1. Strategic Niche Management, business models and the role of demonstration projects

A progressive change from the traditional centralized power generation to a decentralized system with intermittent renewables and storage would constitute a regime change. The socio-technical systems literature describes how changes from one socio-technical regime to another can occur (Geels, 2004). In general, socio-technical systems are stable towards small variations and can, therefore, be inert to change. Prototypes of new regime archetypes can, however, be formed in niches (Geels, 2004). The bud of new regimes are niches, whose growth can eventually lead to regime change. Strategic Niche Management (Kemp et al., 1998) has been developed as a tool to foster such niches and help to achieve the regime change towards sustainable developments. Recently, the ‘business model’ concept has received increased attention within the Strategic Niche Management literature (Huijben and Verbong, 2013), as business models are necessary for the upscaling of novel technologies (Johnson and Suskewicz, 2009). Business models are part of the knowledge creation and formation of niches towards a “dominant design” (Geels, 2011). Recently, Bolton and Hannon (2016) also highlighted the role of business models within socio-technical systems for governing change.

While there are several business model definitions (Massa et al., 2016), the one of Osterwalder (2004); (Osterwalder and Pigneur, 2010) is rather established within the energy policy area (Engelken et al., 2016; Hall and Roelich, 2016; Hannon et al., 2013; Huijben and Verbong, 2013). At the highest level, the definition can be considered as quadripartite, consisting of “value proposition”, “customer interface”, “infrastructure”, and the “revenue model” (Richter, 2012). On a more detailed level, the customer interface can be further divided into “customer segments”, “channels”, and “customer relationships”. The infrastructure consists of “key resources”, “key activities”, and “key partnerships”. Within the revenue model, “revenue streams”, and “cost structure” can be distinguished (Richter, 2012).

Pilot projects play a major role in the development of new business models. This is particularly the case in technology developments (Hellsmark et al., 2016). In fact, many new commercial activities of firms have their origin in projects (Shenhar and Dvir, 2007). Bohnsack et al. (2014), for example, empirically showed how business models for electric vehicles developed out of initial projects. Nevertheless, the study of projects is not only important for practitioners or researchers working on the firm's perspective. Projects play a significant role in the creation and evolution of niches (Schot and Geels, 2008) and can thus be the very starting point of socio-technical transitions. Of equal importance is the fact that practice-based action research is a crucial pillar to ground the mathematical modeling of systems and socio-technical analyses (Geels et al., 2016). In this context, practice-based action research has several merits according to Geels et al. (2016): First, it highlights the role of stakeholder alliances, second, it can unlock drivers beyond mere financial incentives and third, it offers the opportunity for optimization by experimentation. Consequently, Geels et al. (2016) argue that practice-based action research can give valuable feedback to quantitative simulations and socio-technical analyses, which in turn can provide insights on where new demonstration projects are most useful. In fact, in a socio-technical analysis on electricity storage, Grünewald et al. (2012) called for demonstration projects in niche applications to avoid the lock-in to other technologies, because electricity storage is currently facing several institutional and regulatory barriers.

2.2. Electricity storage applications and retail electricity prices in Germany and Western Australia

By reconfiguring the value chain, the notions of the value propositions developed in the traditional centralized system blur, particularly when multiple prosumers are involved. Thus, Hall and Roelich (2016) defined the notion of "complex value" as "the production of financial, developmental, social and environmental benefits which accrue to different parties, across multiple spaces and times, and through several systems." This concept is particularly relevant in the context of electricity storage systems, which can have numerous applications. At the generation level, storage can help to restart conventional generation assets in the absence of power from the grid and also shape the output profile of renewable energy sources (Battke and Schmidt, 2015). The Levelized Costs of Energy (LCOE) of a renewable energy source (Kost et al., 2013), combined with the Levelized Costs of Storage (LCOS) of a battery (Jülch, 2016), are in many cases higher than the wholesale electricity prices of mainland grids in industrialized nations (IEA, 2017). However, a renewable energy source combined with a battery is competitive in remote regions and islands where the alternative would be a diesel generator (Blechinger et al., 2016). At the grid level, electricity storage can be used to hold voltages and frequencies in a district within the specified limits and can provide “reserve capacity,” “transmission & distribution investment deferral,” and “wholesale arbitrage” (Battke and Schmidt, 2015). At the consumption level, storage can increase “end-consumer power quality,” “end-consumer power reliability,” “self-consumption,” and can be used for “end-consumer arbitrage” (Battke and Schmidt, 2015). Numerous studies have analyzed and compared the profitability of the aforementioned value propositions (e.g., Battke et al., 2013; Braff et al., 2016; Eyer and Corey, 2010; Fitzgerald et al., 2015). The “increase of self-consumption,” “end-consumer arbitrage,” “grid investment deferral,” primary, (negative) secondary or (negative) tertiary “reserve capacity” are particularly prominent value propositions when considering both practical implementation and economic viability (Stephan et al., 2016). Recent studies have also shown that a combination of value propositions can benefit overall profitability (Fitzgerald et al., 2015; Stephan et al., 2016).

Many residential PV plus storage systems serve to increase self-consumption. In this application, energy produced on site is stored for subsequent use. This can happen for financial, psychological or ecological motives. In the increase of self-consumption, the system competes with the grid supply and thus retail electricity prices. Germany and Australia are among the countries with the highest retail electricity price increases in recent years (Simshauser, 2016). At the same time, both have seen a tremendous uptake in PV over the past years. In 2012, Germany was the leading country regarding PV capacity per capita and Australia the leading non-EU country (Sahu, 2015). At the end of 2015, there were at least 1.6 million PV installations in Germany (Netztransparenz.de, 2016). Australia had 1.6 million small-scale installations by the end of 2016 (Clean Energy Regulator, 2017). Germany's and Australia's storage markets are therefore particularly attractive (Rubel et al., 2017). Of all the major Australian cities, Perth in Western Australia has the lowest Levelized Costs of Energy (Australian Energy Council, 2016), making PV plus storage particularly attractive there. Fig. 1 shows the retail electricity prices in Germany and Western Australia compared to the LCOS and LCOE estimate for photovoltaics. In Germany, the tax percentage in household electricity prices is the second highest of all IEA member countries. In the second quarter of 2016, 53.3% of household electricity prices were taxes (IEA, 2017). Only Denmark had a higher share (58.5%) in this period (IEA, 2017). As can be seen in Fig. 1, a significant fraction is due to the Renewable Energy Act (EEG) apportionment, which finances the feed-in compensation of qualified distributed renewable generators. Besides the generation costs of 7.35 €ct/kWh, other important components are the VAT (19% or 4.76 €ct/kWh), the electricity tax (~ 2.05 €ct/kWh), the concession fee (~ 1.65 €ct), and grid costs (6.11 €ct/kWh) (Bundesnetzagentur, 2016).

The largest fraction of the retail electricity prices in Western Australia are the network costs with 10.46 €ct/kWh (Australian Energy Market Commission, 2016). Environmental policies add an additional 0.86 €ct/kWh, the VAT adds 2.07 €ct/kWh.

INSERT FIG. 1 ABOUT HERE

In both regions, comparatively high retail electricity prices make PV and electricity storage as a supplement to conventional supply from the grid increasingly attractive, as prices of battery modules are decreasing. Nykvist and Nilsson (2015) calculated an annual reduction rate of 8% for battery electric vehicle modules from leading suppliers. The decline of battery module costs corresponds to reductions in the LCOS. LCOS depend on the application, as applications with high charge-and-discharge frequencies make the use of technologies with a high cycle duration worthwhile, even if the modules are more expensive than those of other technologies. Due to numerous relevant parameters, there are several studies which calculate LCOS for various technologies and applications (Battke et al., 2013; Jülch, 2016; Zakeri and Syri, 2015). The increase of self-consumption has approximately 365 cycles per year. Jülch (2016) gives values for the LCOS between 23 and 37 €ct/kWh for lithium batteries in applications with 365 cycles per year. For lead batteries, she calculates LCES of 15–19 €ct/kWh.

Applying three years of cost reductions to the value of 27 €ct/kWh of Battke et al. (2013) for "Energy Management (community scale)" yields 21 €ct/kWh as an estimate for current storage costs. PV LCOE can be assumed to be around 12 €ct/kWh (Kost et al., 2013; pv magazine, 2014). The sum of the LCOE and LCOS is therefore still slightly higher than the retail electricity price in Germany of 29.80 €ct/kWh (Bundesnetzagentur, 2016). However, studies (Hoppmann et al., 2014; Kaschub et al., 2016) expect economic viability in the near future. Fig. 1 shows that net costs of the sum of LCOS and LCOE are close to grid parity. However, grid parity is only within reach if no additional taxes and fees on the electricity from a combined PV storage system are applied.

2.3. Individual vs. shared storage for neighborhoods

Residential storage systems are an evolving market segment, which has been financially supported by policymakers in countries such as Germany (Kreditanstalt fuer Wiederaufbau, 2013) and Sweden (Steel, 2016). In Germany, for example, around 34,000 systems with a cumulative capacity of more than 200 MWh were put into operation between May 2013 and January 2016 (Kairies et al., 2016). The average storage capacity per system thus amounts to around six kWh. The trend also continued in 2016, and at the end of the year, more than 52,000 systems with a total capacity of 300 MWh had been installed (Enkhardt, 2017). Also, the Australian market is increasingly targeted by prominent manufacturers of residential systems

(Rubel et al., 2017). By contrast, shared storage has received only limited attention so far. This is a surprising research gap because community scale electricity storage has the advantage of adding significant storage capacity to the grid compared to individual end user systems. Compared to large pumped hydro storage, it could nevertheless be installed near the load (Roberts, 2013), minimizing electricity transmission distance as renewable energy systems are frequently installed in smaller settings in rural areas (Kerr et al., 2017).

Fig. 2 gives an overview of the advantages and disadvantages of having a neighborhood with individual storage systems versus one system shared by all homes. Zeh et al. (2014) have argued that, for an equal amount of storage capacity, it is beneficial to have one large storage system rather than the storage capacity being spread over a number of households. They give three distinct reasons for their conclusion: first, having a central storage system is not dependent on overcoming the doubts of end-users installing storage devices within their premises. Second, larger storage systems can participate more easily in power markets. While it is also possible for smaller systems to be combined to virtual power plants, management efforts - and therefore associated financial losses - would be higher for a larger number of small systems. Third, according to Yunusov et al. (2016) and Zeh et al. (2014), the possibility to choose the connection point of community electricity storage systems provides an operational degree of freedom that can be used to increase the voltage quality of the local distribution grid.

In addition to the arguments described above, scaling effects make larger systems favorable from a cost perspective point of view (this argument is also mentioned by Schill et al. (2017)). Since the storage capacity of single-family homes is not used in the absence of their owners or when the charging/discharging limit is reached, a community storage system can be expected to have the same effective storage capacity even with a capacity that is lower than the sum of private storage systems in individual households. Fares and Webber (2017) have shown that the inefficiencies of home storage can lead to increased electricity consumption and indirectly to increased emissions. A shared operation would average out the variances of the users. For uncorrelated behavior, this follows out of the Law of Large Numbers, as the standard error decreases with a larger sample size. The degree of correlation between the households thus influences the benefits of shared operation. The shared service would be particularly beneficial for uncorrelated households. As the schedules differ among all households at least to some extent, shared service will be advantageous compared to an ensemble of individual storage systems in most scenarios. This is in accordance with the results of Parra et al. (2015), who calculated that the possible LCOS reductions could be as high as 29% to 44% by changing from one household to a 5-household community. Next to sharing storage between different users, sharing between various applications can also be beneficial (Lombardi and Schwabe, 2017). In addition, advantages of cooperative schemes have been shown for demand response (Rieger et al., 2016). The apparent benefits of shared usage has attracted interest, and several technical papers simulating such systems have been published (Dimitrov et al., 2016; Khalilpour and Vassallo, 2016; Lee et al., 2014; Li, 2016; Tushar et al., 2016; Wang et al., 2013).

INSERT FIG. 2 ABOUT HERE

Next to the increase of self-consumption, storage systems can also reduce peaks on the grid, and thus help in the deferral of grid extensions. However, at the “macro level” (Devine-Wright et al., 2017), the system costs often still exceed those for a network extension; especially in the case of transmission grids (Fürsch et al., 2013). Nevertheless, smaller battery storage systems can help to reduce costs in comparatively expensive distribution network extensions (Steinke et al., 2013). Studies have noted that distribution grids, in particular, require extension investments (Agricola et al., 2012). Price signals of peak demand charges (e.g., Jahn, 2014) support this reasoning: they are usually higher in low voltage networks compared to medium or high voltage networks. For this application, the optimal size of a battery storage device is thus on an order of magnitude of transformer substations of low voltage distribution networks. For systems with higher power ratings, network extensions become favorable, limiting the benefits of large central storage systems. On the smaller end of the spectrum, storage becomes finer grained than the needed capacities and would thus not be optimized regarding economies of scale. Precisely for the "meso level" (Devine-Wright et al., 2017), models for community level storage are needed and are the focus of our research.

Next to the technical scales, social factors cannot be neglected either. Communities around the globe play an increasingly important role in the adoption of novel energy technologies (Bauwens et al., 2016). First, cooperatives provide an additional channel for capital flow into sustainable energy technology. Second, community ventures can lead to increased citizen engagement, which according to Viardot (2013) reduces adoption barriers, especially if they are combined with benefit payments to the local community (Kerr et al., 2017).

Both capital flow, as well as civic participation for storage, could support the deployment of electricity storage. Indeed, the topic is gaining traction among practitioners: In the U.S., the Community Storage Initiative (2017) calls for "business model[s] and best practices around 'Community Storage'". In Germany, the term "Quartierspeicher" [neighborhood/community storage] attracts the interest (Gaudchau et al., 2016) of users as several pilot projects have been implemented. Such schemes would allow citizen engagement in the diffusion of electricity storage and provide additional investment possibilities. The investigation of shared electricity storage at the neighborhood level is thus a pressing need for research.

3. Materials and methods

3.1. Cross-case study

We chose a qualitative case study as a research method for several reasons. First, due to the exploratory character of our analysis, it was a favorable method. An open exploratory approach was considered a good fit to address regulatory issues. Second, it was also the method of choice as we were investigating a contemporary phenomenon over which we have little to no power (Yin, 2014). Last but not least, we also believed that even if merely illustrative, there would be merit in this study (Siggelkow, 2007). We carried out a cross-case study as this research design enables cross-case synthesis (Yin, 2014) and can be more robust than single case studies (Eisenhardt and Graebner, 2007).

Our research consisted of two phases. We first gathered a rich collection of documents of all of the projects. After document screening and initial coding, we designed a semi-structured guideline and conducted interviews with at least one participant per project. Table 1 gives an overview of the collected sources for every project.

3.2. Document analysis

Our primary data source were project-related documents. Bowen (2009) discusses several benefits that the analysis of documents can offer: Among others, they provide means to triangulate evidence from other sources such as expert interviews. An important factor is that documents can help researchers to prepare interviews more specifically. Where different versions of a document exist, small changes can reflect significant developments. This can allow insights into the evolution over time as well as the different viewpoints of individual stakeholders.

To collect project-related materials, we first searched intensively for websites, presentations, magazine articles, blog posts and published reports using conventional internet search engines.

In the projects in which this approach did not yield a sufficient amount of material, we searched for articles in magazines and periodicals using the GBI Genios Wiso and Dow Jones Factiva databases. In the next step, we searched for videos and TV recordings. We collected the relevant documents in the qualitative analysis software MaxQDA and categorized them by different document types. We also sorted the material by date of issue to allow insights into the evolution of the projects over time. After collection, we reduced the material to the essential content by removing additional pages and cut the videos down to the project-relevant segments.

INSERT TABLE 1 ABOUT HERE

3.3. Expert interviews

After collecting the documents as described in section 3.1, we gathered the persons mentioned in them in a table. We then contacted one person per project with the request for an expert interview. We preferably contacted individuals who likely had an active role and thus detailed knowledge about the project. If the individual did not answer, we sent a reminder and additionally sent a request to another person affiliated with the project. While we also relied on previous contacts with affiliated organizations for recruiting two candidates, none of the interviewees were known to us in advance. We also asked them whether they knew other individuals involved in their project who could be relevant for our study.

The semi-structured guide consisted of several blocks developed in parallel to the initial coding of the documents. The first block of questions dealt with the interviewee’s qualifications and role in the project. This block was followed by a block on business models. It was started with an open question for the interviewees to describe a business model that could be generalized out of the project. The main block consisted of nine questions regarding each business model component according to Osterwalder and Pigneur (2010). Regarding the value proposition, we asked more detailed questions, in which we explicitly wished to know whether it served one of the six applications as detailed by Stephan et al. (2016). Also, on the cost side, we subdivided the question into capital expenditures (CAPEX), operational expenditures (OPEX) and the obligation to pay other grid-related fees and taxes. An obstacle block followed the business model block. Like in the case of the business models, it was opened by an open question on barriers. In the following, we systematically asked for different barriers according to the framework by Painuly (2001). The final part of the questionnaire consisted of several closing questions that asked, among other things, whether the interviewees could recommend other individuals of the project for the survey.

The first author of the paper conducted all interviews in November and December 2016. The shortest recorded interview used for analysis lasted around 27 minutes; some took up to slightly more than one hour. All interviews were carried out telephonically except for one, which was conducted face-to-face. The latter interview was the only one where two interviewees were questioned at the same time as they insisted on doing so. One interview (not listed in Table 1) was discarded as the person we were referred to only had general knowledge on energy storage but had not been involved in the project we were investigating. We recorded and transcribed all interviews listed in Table 1. Afterwards, we qualitatively analyzed the interviews in MaxQDA next to the other documents of each project.

4. Selection and description of cases

4.1. Project selection

In Germany, we mainly searched for projects using the keyword “Quartierspeicher” [quarter storage]. Here, we focused on projects with a rated power below 1 MW, as higher systems usually qualify for participating in balance energy. We also neglected projects with a size smaller than 100 kWh, as many of these serve similar applications such as residential applications just for commercial settings. Table 2 gives an overview of the projects and their key features. In Western Australia, we searched for projects using the term "Community energy storage". For Australia, numerous sources led to the Alkimos Beach trial. Several articles discussing it also mentioned the White Gum Valley project as another important Australian project. While we did not find the project in Speyer during our initial search for "Quartierspeicher" in Germany, we included it as it demonstrates a community storage approach. In total, we selected eight projects. The sample does not aim to be exhaustive but aims to be large enough to make the case that the findings are of broader relevance while allowing a detailed and illustrative analysis of each project.

4.2. Projects

INSERT TABLE 2 ABOUT HERE

4.2.1. The Alkimos Beach Trial

The Alkimos Beach Trial is a demonstration project with a capacity of 1100 kWh in a new housing development in Western Australia. The project is in the process of installing more than 100 smart home devices in the community. The project documents highlight that there is no actual way for how storage systems can be compensated within communities and that the project seeks to develop solutions in this area. The project developed the Peak Demand saver plan, which is offering virtual electricity storage to residents with PV.

4.2.2. Am Umstädter Bruch

As part of the Flex4Energy project, a system with up to 800 kWh will be installed in a neighborhood of the town of Groß-Umstadt in the German state of Hesse. Each of the 80 newly built houses in the area has to install at least five kW_p of photovoltaics. The storage unit will make residential storage systems redundant in the neighborhood. Households in the vicinity will get a smart meter unit installed and will be able to see their generation and consumption data in an online portal.

4.2.3. Epplas

Epplas is a small village in northern Bavaria with 16 households. 13 of them operate PV modules with a total capacity of 287 kW_p . A project consortium with state level funding has installed a lead battery storage system with 330 kWh and 70 kW to buffer local peaks and test various applications.

4.2.4. Living Lab Walldorf

The project aims to test new applications and digital technologies. At the time of data collection, it was still in the earlier project stages. As part of the trial, a 100 kWh storage system will be installed in a neighborhood. It will be the original system from the Strombank project, which has been moved. The project stresses that it operates outside the current regulatory framework to test new applications.

4.2.5. Smart Community Speyer

The Smart Community project is a pilot project in the town of Speyer in Baden-Württemberg, Germany. The consortium consists of Stadtwerke Speyer (the local utility), the Japanese New Energy and Industrial Technology Development Organization (NEDO) as well as other providers. In one apartment building, a storage capacity with a sum of 230 kWh will be shared in the entire house. In an additional housing development nearby, the storage system will be partitioned into separate units of 6 kWh for each apartment.

4.2.6. Strombank

Strombank aimed to demonstrate a banking-like model with 116 kWh in a neighborhood of the city of Mannheim, Germany. The idea is that the 14 households and four firms in the vicinity can use the system for shared storage. Each user had several types of accounts, a regular giro/checking-like account, but also an investment depot-like account, where the electricity could be traded at the energy exchanges, generating additional revenues. An app visualized the balance each user had. While the project received considerable attention and awards, the storage system has been moved to the site of the LiLa Walldorf project, as the costs due to taxes and fees alone would have amounted to 22 €ct per stored kWh and thus prohibited profitable operation.

4.2.7. White Gum Valley

White Gum Valley is a suburb of Perth in Western Australia. The project seeks to demonstrate a shared operation of storage and PV by the strata company. A strata corporation is a legal form which can be used to regulate ownership of multi-household complexes (Department of the Premier and Cabinet of Western Australia, 1985). In the model of the project, the strata company becomes a quasi-utility, as the households have their power delivery contract with it. The households pay a daily charge depending on their peak power as well as a unit price for every kWh. The strata company buys residual electricity from the grid.

4.2.8. Quartierspeicher Weinsberg

Weinsberg is a town close to Heilbronn in Baden-Württemberg. In the new residential development consisting of 23 households, several state-of-the-art energy technologies are installed next to battery storage, 145 kW of PV, energy management, and thermal storage, among others. A small holding company owns and operates the PV plant while the homeowners’ association owns the grid.

5. Cross-case analysis

5.1. Key design possibilities

5.1.1. Value proposition

Regarding the value proposition of the storage system, almost all projects more or less explicitly state that they aim to increase local consumption. Only the interviewees for LiLa Walldorf did not confirm that their project serves the purpose of self-consumption increase, but the results of a survey carried out by the project organizers, shows that the participating households expect this. Besides local consumption, several projects also aim for additional value propositions. Some have qualified or simulated to provide additional value propositions such as reserve capacity.

5.1.2. Customer interface

Two key differences can be seen regarding the potential customer segment. Strombank, Alkimos, Umstädter Bruch, and LiLa Walldorf aim at households which already own (or will individually own) PV on their rooftops such as single-family homes. On the other hand, there are also projects targeting (customers in) denser developments, such as Weinsberg, White Gum Valley and the Smart Community Speyer.

The first four projects mentioned above employ the public grid as a channel to deliver their value proposition. At least the German projects in this group, however, reported significant regulatory barriers, which are discussed in section 5.2.3.

Particularly for these projects, information and communication technologies (ICT) play a major role in the customer relationship management. One of LiLa Walldorf’s core project missions is the investigation of suitable software and internet technologies. Also, the different accounts in the Strombank project are displayed via an app. The goal of the Alkimos project is the installation of at least 100 energy smart home packages. The information systems help to deliver customers the feeling of consuming self-produced electricity also at times when their PV module is not generating electricity.

5.1.3. Infrastructure

The difference in addressed customer segments is also reflected in the infrastructure. Storage projects targeting single family homes with existing PV modules do not operate PV themselves. In contrast, in the Weinsberg, White Gum Valley and Smart Community Speyer projects, a member of the project consortium operates the PV modules.

Regarding key resources, one key differentiator next to the ownership of generation resources is also given by the grid. White Gum Valley, the Smart Community Speyer as well as the Weinsberg project all share in common that the grid connecting the PV, storage and households is on the customer premises, i.e., it can be considered a microgrid.

There are also different approaches regarding partitioning. The Weinsberg, Alkimos Beach, White Gum Valley, Walldorf and Epplas projects all treat the system as one logical unit. In contrast, Am Umstädter Bruch, Strombank and the Smart Community Ginsterweg trial as part of the Smart Community Speyer differ from the projects in this category by the fact that the system is partitioned, i.e., there are individual partitions or accounts per user.

5.1.4. Revenue model

All projects have public funding in common, so the current main revenue is stemming from R&D grants. Alkimos, White Gum Valley, Weinsberg, and the Smart Community Speyer write invoices according to the model. The other projects bill users according to conventional power supply (as if no storage system existed) and therefore simulate possible revenues.

One of the key differences with respect to the costs - and thus to the viability of the models - is due to the different regulatory treatment of public grids and micro-grids. In the projects that employ a microgrid, the operating entity can avoid paying many of the additional fees incurred in retail electricity costs.

Morphological boxes are a customary tool to describe business model possibilities holistically for a new technology (Kley et al., 2011). Fig. 3 shows the important configuration possibilities mentioned above as a morphological box.

INSERT FIG. 3 ABOUT HERE

5.2. Investigation of barriers

We were looking for evidence of all types of barriers in our material. We applied the framework by Painuly (2001) and specifically looked for “1. Market Failure/imperfection”, “2. Market Distortions”, “3. Economic and Financial”, “4. Institutional”, “5. Technical”, “6. Social, Cultural and Behavioural” and their subcategories, as well as those which did not fit any of the aforementioned categories. The sections below give an overview of the most significant findings.

5.2.1. Minor role of social, cultural or behavioral barriers

It was remarkable that seven interviewees expressed the absence of social, cultural or behavioral barriers or even the opposite, i.e., the prevalence of a high acceptance and interest by the local residents. When being asked “Are there any social, cultural or behavioral barriers to the adoption of the model?” an interviewee from the Strombank project, for example, answered:

> *STB_B: "[...] No, so actually quite the opposite, so we were very surprised about the high acceptance [transl. from German] [...]"*

This indicates that community effects could thus serve as drivers of such models, which is in accordance with other current studies on community initiatives (e.g., Melville et al., 2017).

5.2.2. Battery costs

While many interviewees mentioned that battery costs have come down significantly in recent years, the net LCOS are still a significant barrier towards economical operation. The Weinsberg storage system costs €180,000 for 150 kWh. EPL_A mentioned around €1000 per usable kWh. The LiLa project interviewees mentioned €140,000 with a 5-year depreciation. Strombank calculated net storage costs with 600 €/kWh currently and 500 €/kWh by 2020 (Thomann et al., 2016). Taking the lowest value, 500 €/kWh, and assuming one cycle per day and a battery lifetime of 10 years, we get approx. 16 €ct/kWh, which shows how hard it is to achieve a viable business model. This reasoning is also supported by SCS_A, who, when being asked about the CAPEX, stated:

> SCS_A: "*Well, I can't say anything about that, except that it is so high right now that it does not allow economic viability. [transl. from German]*"

5.2.3. Lack of a suitable regulatory framework for the use of the public grid

The document analysis revealed that the lack of an appropriate legal framework is a major obstacle to the broad adoption of shared models. In Australia, the absence of an adequate framework is mentioned to justify the relevance of the Alkimos Beach project: *"There are currently no existing tariffs to allow community energy storage to discharge onto electricity networks."* Also, the Epplas project discusses the renting of storage capacity to local households but mentions that it is forbidden (PV-Magazine, 2015).

The German projects, which seek to implement their approaches within the current framework, are facing prohibitory high costs. The Strombank project mentions the obligation to pay taxes and fees of 22€ct/kWh on top of the technology costs (Thomann et al., 2016), which renders the model unattractive under the current framework. Both surveyed persons of the Strombank project have confirmed the problems associated with the use of the public grid in subsequent interviews.

> STB_A: *"Yes, that is [...] the big challenge with the system. In our case, this was the public grid, thus, of course, the business model is dead, to be honest. It is, however, also possible to run it as a customer installation and thus the installation or the grid belongs to the object owner, for example. [transl. from German]"*

When being asked about „which barriers are hindering a broad adoption of models similar to yours?" other German projects relying on the public grid, e.g., LiLa Walldorf, unambiguously mentioned taxes and fees as significant barriers.

> LLW_A: *"Yes, as I said several times, the charging and discharging fees make the operation of the storage system uneconomical [transl. from German]"*

Several interviewees also mentioned that they are uncertain about which components of retail electricity prices are actually applied. When trying to combine the application of delivery to households with other grid-supporting applications, the unbundling is also mentioned as a barrier:

> EPL_A: *"To meet the voltage limits where there are many renewable energies, this is a strategy that leads to a relatively low annual usage. And, consequently, it is not really economical compared to conventional grid expansion measures. But if then somehow a network operator wants to offer any tariffs for households at the same time, he infringes the unbundling [transl. from German]"*

5.2.4. Lack of experience with microgrid setup and operations

On the other hand, in the case of Weinsberg, which relies on a proprietary grid between households, we could not find evidence that would support the existence of the barriers mentioned in the previous section. However, an interviewee mentioned the limited experience of distribution network operators (DNO) with private grids as barriers:

> WNB_A: *"[...] the utilities and network operators themselves do not really know how to manage such private networks. And I think we have partly put in too much effort. [...] This means that the [...] measurement concept is unnecessarily complicated so that the costs were correspondingly high. [transl. from German]"*

The statement suggests that there is little knowledge or willingness to set up and manage microgrids among DNOs. This reasoning was also supported by quotes in an article on the White Gum Valley project "*Barriers include getting approvals from Western Power[...]*". Because classification as customer installation can reduce the obligations to pay grid-related fees, supporting the setup of such configurations is not necessarily in the interest of DNOs.

5.2.5. Miscellaneous barriers

In addition to the aforementioned barriers, difficulties with aligning financial incentives and a lack of them has been mentioned by several projects as obstacles. Furthermore, several interviewees expressed difficulties with data exchange standards. It is, however, likely that those standards will evolve as the technology spreads. Besides, one project stressed the expensive fire protection efforts as a barrier to replication.

5.3. Exemplary models

5.3.1. Sharing between detached houses through the public grid

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INSERT FIG. 4 ABOUT HERE

Fig. 4 shows one possible model based on the design possibilities. In a neighborhood where several households own and operate rooftop photovoltaic modules, a container-sized storage system could be installed to deliver the increase of local/self-consumption as a primary value proposition. An information system could show the usage of the individual’s storage partition and thus deliver additional non-physical value propositions such as perceived autarky. This could be arranged as individual accounts (e.g., as in the Strombank project) or as a simulated household system, for example. The ideal dimension of the storage partition or account and possible applications depend on a household's generation and demand pattern. Households using electricity for heating often need less storage capacity compared to households which use other energy forms for heating. It would, therefore, be reasonable to offer different storage partition sizes depending on the heating technology of the households. While the optimal dimensioning is also an issue for regular residential systems, a shared system could optimize it seasonally for every household.

A key activity in this model would be energy storage, for which the storage operator would need to have a system. It would also be conceivable for the households to own or lease the individual storage units. The storage operator would need a partnership or at least an agreement with the district network operator for the use of the grid.

Revenues could come from renting a fraction of the storage for a monthly or annual fee (such as in the case of the Power Saver tariff in the Alkimos Beach Trial), from selling electricity to the customers or from additional activities such as the participation at markets for reserve capacity.

Next to the CAPEX for the storage cells, costs and taxes for grid usage are equally important factors for the economic viability of the model. The Strombank example shows that these can be up to 22 €ct/kWh (Thomann et al., 2016) in Germany due to the regulatory framework. For Western Australia, the question remains what fraction of the network costs of 10.46 €ct/kWh would have to be paid if a storage operator (other than Synergy or Western Grid) would set up such a model.

5.3.2. Sharing within a microgrid behind the utility meter

INSERT FIG. 5 ABOUT HERE

The previous model has significant barriers. The use of the public grid adds high economic and bureaucratic burdens due to the applicable taxes and fees. Models where the microgrid is behind the utility meter and qualifies as customer installation, on the other hand, do not have the same legal constraints. This setup is also employed by some cooperatives to provide renewable energy to tenants at competitive prices (Schäfer, 2012).

In Germany for example, customer installations can qualify as a “Kundenanlage” or customer installation, a term defined in the Energy Industry Act (Ortlieb and Staebe, 2014). Grids in apartment buildings and larger housing blocks can qualify for this legal treatment. Spatially adjacent (single) family housing developments, such as in the case of Weinsberg, can also fulfill the criterion. Therefore, all new or existing multi-family household developments and adjacent single houses with the option for a proprietary microgrid could be targeted as this model’s customer segment. Operating within these premises, a legal entity, e.g., a cooperative of residents, or the housing administration, could buy, install, and operate PV panels on or in the proximity of buildings and sell the electricity to the users. This model is depicted in Fig. 5, which shows that storage could be on the premises of the private grid but could still be operated jointly. While not indicated in Figure 5 a, it would be customary to extend the model with a combined heat and power plant (CHP) fueled by natural or biogas, thermal storage and a heating object grid such as in the example of Weinsberg. This can be beneficial in geographic regions with winter snowfall, as higher amounts of heat generated by a CHP are particularly useful during the same season when the power yield of solar panels is reduced.

In contrast to detached houses, PV is still underrepresented in apartment buildings. Therefore, the key activity would not just be the storage of energy, but also the generation and delivery of electricity and possibly heat. The model can likely only be set up in partnership with the property developer or the housing administration. Key resources of the model would be renewable energy technology such as PV, the microgrid, and the storage system. The main revenue stream of the entity operating the model is given by the selling of electricity (and potentially heat) to the households. The main costs result from the acquisition and maintenance of the different systems. In contrast to the model described before, fees and taxes would be significantly lower than those described above.

6. Conclusions and policy implications

We have investigated projects that provide shared electricity storage for several households. If policymakers make no regulatory adjustments, shared electricity storage will remain a niche for new housing developments, which can set up holistic models based on the ownership of the grid connecting the households. However, the models could be promising if adjustments are carried out to remove the barriers from sharing over the public network. Next to removing tax burdens, policymakers also need to clarify the regulatory framework. A comprehensive framework enabling a clear business case would help to increase investments in electricity storage.

6.1. Implications for the replication of the models

One conclusion of our research is that schemes for community electricity storage, including the usage of the public grid, are currently difficult to implement because additional fees apply. These results can likely be transferred to other countries where taxes make up a significant portion of retail electricity prices, such as Denmark, Italy or Portugal (compare (IEA, 2017)). In these jurisdictions, the distinction between net and gross storage costs becomes important for grid parity forecasts of storage costs. In contrast, the economic viability of electricity storage - and therefore the market development - is still further away in countries with lower retail energy prices. However, once costs of storage systems decrease further, sharing electricity storage (as in the investigated cases) will be even more attractive in such jurisdictions, as the sharing barriers become smaller.

What is possible now in jurisdictions with high grid-associated taxes and fees is that pilot projects of shared storage systems try to establish profitable business models within large apartment buildings or new housing developments, where the last meters of the grid can be realized in private possession, and therefore most of the grid fees and taxes do not apply. Also, new housing developments can plan a holistic energy supply that includes electricity storage by setting up a microgrid. Countries that also have a strata title can seek to increase the implementation of models similar to the one in the White Gum Valley.

6.2. Long term policy

Currently, the regulatory framework favors private household systems, despite the fact that there is no evidence that smaller systems are more beneficial to sustainable energy systems. Policymakers should thus evaluate options on how to adjust taxes and fees so community electricity storage becomes a realistic option. Currently, projects employing the public grid simulate, rather than fully implement, novel business models. Greater flexibility and fewer fees would certainly support the dissemination of electricity storage systems. In addition, more attention should be paid to distribution grid control. Easier access for all parties to the distribution network is essential for transparent and efficient markets.

Our findings also have implications for social issues related to sustainable energy. High retail electricity prices in countries with high shares of renewable energy make energy poverty an increasingly important issue. At the same time, tenants are still less likely to own photovoltaics and other renewable generation technologies due to a lack of capital, spatial limitations or a lack of the property owner's approval, among other reasons. Improving the feasibility of shared storage business models would help to avoid the same scenario for the diffusion of storage technologies and contribute to social innovation.

A more general issue that remains to be addressed is where electricity storage will be placed in future electricity value chains. Presently, the energy value chain is often defined as generation, distribution, transmission and consumption (Bradbury, 2014). For each link of the chain, legislation is rather sophisticated. Storage, however, can be similar to generation when discharging, support the stability of transmission and distribution grids, and temporarily act like consumption when being charged. Without clarifying the role of energy storage, certain models could be subject to double taxation and thus remain a niche with limited potential for growth.

There is evidence that shared storage could reduce costs compared to individual storage. Further legal research should investigate how the revealed barriers could be removed. In particular, more research is needed regarding how the formation and governance of microgrids can be facilitated. In any case, all policies influencing the feasibility of models have to be carefully evaluated as policies favoring either one would shape the energy system for decades to come.

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9. Figures and tables

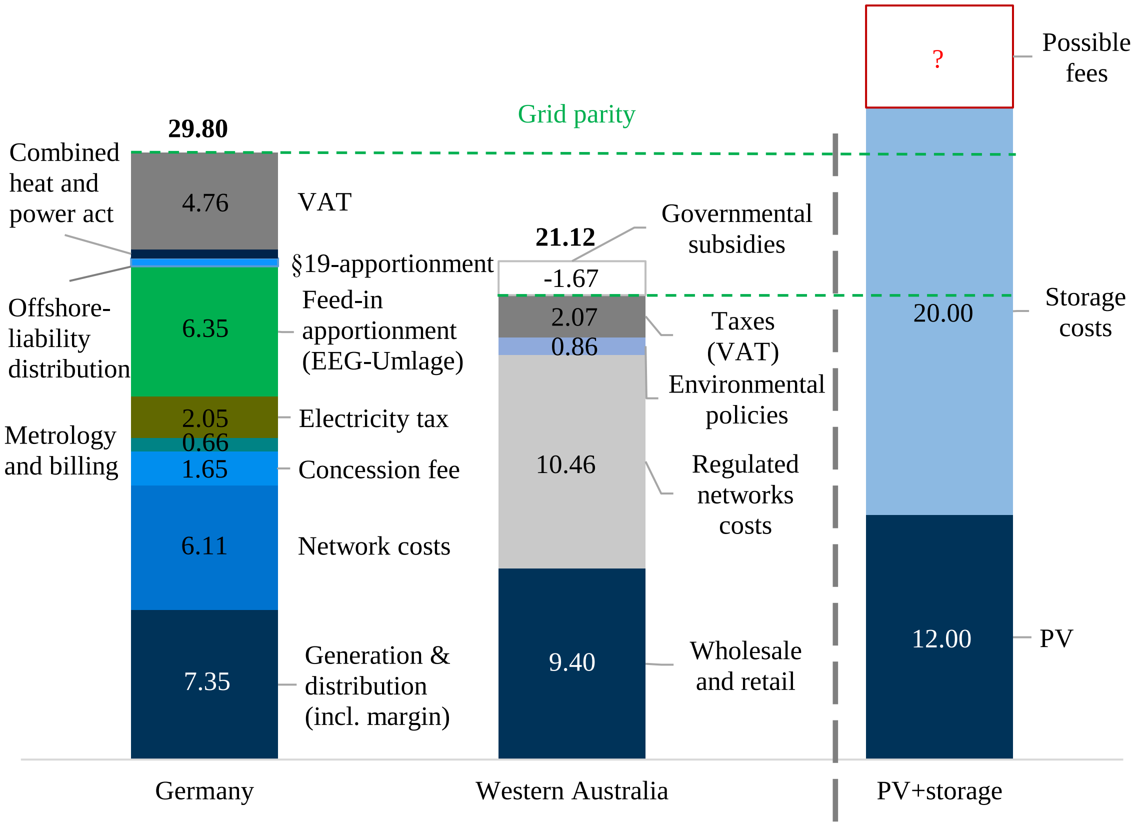


Fig. 1. Retail electricity prices in Germany (Bundesnetzagentur, 2016) and Western Australia (Australian Energy Market Commission, 2016) and estimates for storage costs (Jülch, 2016) and PV (Kost et al., 2013)

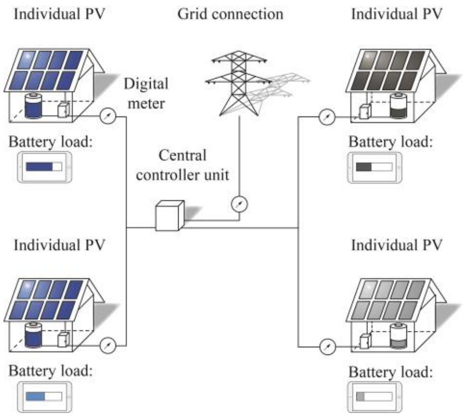
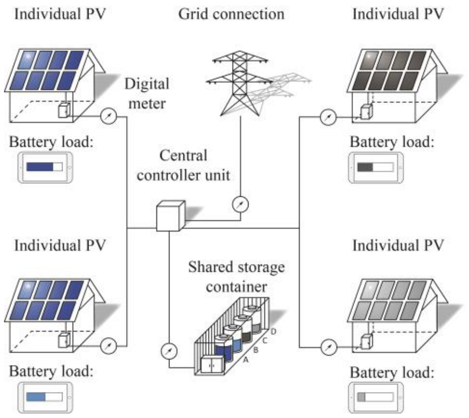
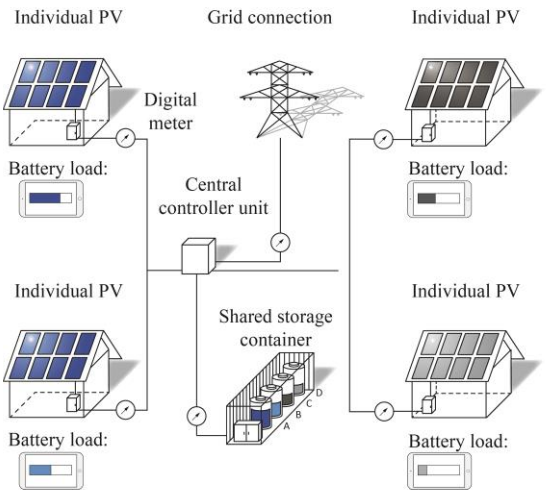
	a)	**b)**
Scenario		
Advantages	• Possibility to participate in power markets when combined to virtual power plants (Zeh et al., 2014) • Less affected by power grid regulations	• Usage by several households reduces LCOS (Parra et al., 2015; Parra et al., 2017) • Can be shared not only between users but also between applications (He et al., 2011; Lombardi and Schwabe, 2017) • Smaller costs per kWh due to scaling effects (e.g., Schill et al., 2017) • Connection point can be chosen individually to increase voltage quality of local grid (Zeh et al., 2014; Yunusov et al., 2016)
Disadvantages	• Doubts of end-users about battery technology in their homes (Zeh et al., 2014) • Individual storage systems are costly (Zeh et al., 2014)	• Affected by complex power grid regulations (Zeh et al., 2014) • Difficult to set up without cooperation or approval of district network operator (DNO)

Fig. 2. a) Neighborhood where individual households own PV plus storage b) neighborhood where individual households own PV but share a storage system

Characteristic	**Configuration**							
Value proposition(s)	Power generation	Heat generation	Increase of self-consumption	Grid investment deferral	Secondary reserve capacity	Primary reserve capacity	Enduser arbitrage	Whole-sale arbitrage
Customer segment(s)	Prosumers with PV	Housing developments and their residents	(Small) Businesses	Public sector	DNO			
Customer channel(s)	Channels of utility	Public grid	Micro-grid	Process of renting or buying property	Convention-al media	Digital	Personal contact on site	
Customer relationship(s)	Digital	Utility	Municipality	Onsite events and workshops	Real estate developer / administration			
Key resources	RET	Microgrid	Battery storage	Smart meter	Heating storage tank	Heat generation technology		
Key activities	Storage of electricity	Power generation	Heat generation	Storage of heat	Smart metering			
Key partnership(s)	DNO	ESCo	Component manufacturer	Housing development stakeholders	Utility			
Revenue streams	Rent for storage capacity	Public project funding	Sale of electricity	Sale of heat	Reserve capacity	Fee for peer-to-peer marketing	Spot market	
Cost structure	CAPEX	OPEX	Taxes and fees					

Fig. 3. Most important configuration elements of shared storage models

a)

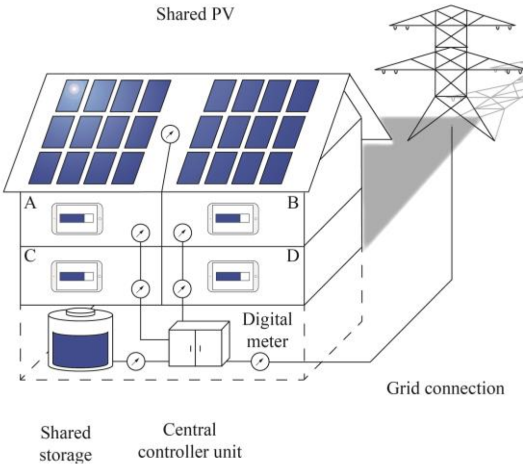


b)

Value proposition	Increase of self-consumption
Customer segment	Prosumers in the vicinity
Customer channel	Electricity delivered through public grid, energy information via apps
Customer relationships	Digitally and onsite
Key resources	Battery storage system, smart meter
Key activities	Storage of renewable energy produced by households
Key partnerships	With DNO for use of the public grid
Revenue stream	Renting of storage partitions for a monthly/annual fee, and potentially through provision of balance services
Cost structure	CAPEX and OPEX for storage system, fees and taxes for grid use

Fig. 4. a) Shared storage within a neighborhood of single family houses b) Possible business model for the implementation

a)



b)

Value proposition	Power generation, increase of self-consumption
Customer segment	Buyers or renters of a property in a housing development
Customer channel	Electricity delivered through microgrid, energy information via apps
Customer relationships	Onsite and digitally
Key resources	Renewable energy technology, microgrid, storage (and possibly heating technology) owned by housing administration, cooperative or strata
Key activities	Generating, storing and delivering electricity
Key partnerships	With property developer and housing administration for setup and operation of the model
Revenue stream	Electricity and possibly heat is sold to households
Cost structure	CAPEX and OPEX of storage system, RET, microgrid. Reduced/no taxes for microgrid use.

Fig. 5. a) Shared energy storage system operated in a microgrid, e.g. within an apartment building (partially inspired by Schaefer, 2012) b) Possible business model for the implementation

Table 1 Data sources and types

Project	**Documents**									**Interviews**
	WP	**PR**	**PE**	**PT**	**MG**	**VD**	**RE**	**OT**	**#**	**Interviewees and pseudonyms**
Alkimos (ABS)	3	5	1	1	0	2	1	2	1	Person involved in the project (ABS_A)
Am Umstädter Bruch (AUB)	5	0	1	0	1	1	1	1	2	(a) Person involved in the project (AUB_A) (b) Person involved in the project (AUB_B)
Epplas (EPL)	3	1	0	1	2	0	0	2	1	Research fellow (EPL_A)
LiLa Walldorf (LLW)	15	1	1	0	0	0	1	0	2	(a) CEO of utility (LLW_A) (b) Two other persons involved in the project (LLW_B and LLW_C)
SC Speyer (SCS)	2	4	2	1	0	0	0	0	1	A team leader of the utility involved in the project (SCS_A)
Strombank (STB)	4	1	3	3	3	2	2	1	2	(a) Innovation manager of utility (STB_B) (b) Research group leader with affiliated university (STB_B)
White Gum Valley (WGV)	7	1	1	0	1	2	1	0	2	(a) Research fellow (WGV_A) (b) Research fellow (WGV_B)
Weinsberg (WNB)	0	0	0	3	3	2	0	1	2	(a) Former division manager with company involved in the project (WNB_A) (b) CTO of firm involved in the project (WNB_B)

WP=Webpage, PR=Press release, PE=Article in periodical, PT=Presentation, MG=Article in (Web-)Magazine, VD=Video, RE=Report, OT= Others

Table 2 Overview of the investigated cases

Case [country]	**Alkimos [AUS]**	**Am Umstädter Bruch [DEU]**	**Epplas [DEU]**	**LiLa Walldorf [DEU]**	**Strombank [DEU]**	**Speyer [DEU]**	**White Gum Valley [AUS]**	**Weinsberg [DEU]**
Battery	Lithium	Lithium	Lead	Lithium	Lithium	Lithium	NA	Lithium
capacity [kWh]	1100	800	330	100	116	230 & 16x6	Total of 300	150
Power [kW]	500	250	70	100	100	45 & 16x6	80	120
PV capacity in vicinity	NA	> 25 x 5 kW_p	13 units total of 287 kW_p	NA	ca. 8x4 kW_p	41.6 kW_p & 46.8 kW_p	Total of 150 kW_p	145 kW_p
Households	>100 with PV	80 (25 with PV)	16	40	14 (and 4 firms)	16 & 16	14	23

2.4. Essay 4 – Measuring and mapping the emergence of the digital economy: A comparison of the market capitalization in selected countries

Full reference:

Müller, S. C., Bakhirev, A., Böhm, M., Schröer, M., Krcmar, H., & Welpe, I. M. (2017). Measuring and mapping the emergence of the digital economy: A comparison of the market capitalization in selected countries. *Digital Policy, Regulation and Governance*, *19*(5), 367-382.

Abstract:

Despite plenty of studies comparing ICT adoption and infrastructure as well as innovation hubs between countries, no research exists which quantifies the digital economy comparatively between countries using representative samples. We present a methodology to identify firms of the digital economy in a given country. We measure the market capitalization of the digital economy of the US, Germany, the Republic of Korea and Sweden in comparison over time. We find that the US lead both in absolute as well as in relative terms. The eleven firms with the largest market capitalization are all American. For Germany, the results show that policy measures should be undertaken to ameliorate competitiveness in the field. The methodology could be applied to other countries which seek to benchmark their performance and derive policy measures to be able to compete with jurisdictions leading in the digital economy. We conclude the paper by providing avenues for future research regarding the measurement of the digital economy.

Author contributions:

S.C.M. is the first author of the publication; A.B., M.B., M.S., H.K., and I.M.W. are contributing authors. S.C.M. developed the research design. Data was collected by S.C.M. and A.B., supported by M.S. S.C.M. conceived the illustrations of the research results. S.C.M. wrote the manuscript, receiving suggestions and feedback from all co-authors. S.C.M. carried out the submission process and correspondence.

2.5. Essay 5 – Digital World

Full reference:

Müller, S. C., & Welpe, I. M. (2017). Digitale Welt. In P. Kenning, A. Oehler, L. A. Reisch, & C. Grugel (Eds.), *Verbraucherwissenschaften* (pp. 261-277). Wiesbaden: Springer Fachmedien.

Abstract:

In the consumer sciences in previous years, the digital world was primarily a term for Internet and telecommunication services. However, digital technologies have now penetrated all sectors. This has increased the economic and strategic importance of data in all value chains. Due to the increased value of personal data, there are now many services that consumers can use without paying, using personal data. However, scientific insights to quantify the value of data and studies on consumer awareness about the value of the data have been limited. In such, greater transparency could create a market for data-intensive services. This context raises many questions for consumer science and policy.

Author contributions:

S.C.M. is the first author of the chapter; I.M.W. is a contributing author. S.C.M. collected and reviewed the references. S.C.M. wrote the manuscript with suggestions and feedback from I.M.W. S.C.M. carried out the submission process and correspondence.

3. Discussion and conclusion

3.1. Findings and contribution

The essays presented in the previous section have numerous findings and contributions. Among others motivated by the still-existing competition between technologies for stationary storage (Battke et al., 2013), Essay 1 found a strong increase in lithium ion battery-related patents—much stronger than in other technologies competing for the use for stationary energy storage. With this finding, it has forecasted improvements in lithium-ion batteries. Furthermore, we found a strong position of Asian countries, particularly the Republic of Korea and Japan. Methodologically, it has been one of the first studies to employ the novel CPC system for monitoring of competing technologies.

Essay 2 showed the differential effect of knowledge networks on different types of innovation: It demonstrated that modular product innovation increases with increased knowledge decomposability. It was found at the same time that the increasing decomposability has a U-shaped relationship with architectural innovation. The finding of differing effects of the knowledge network structure on technological innovation also calls into question whether, and to which extent, theories concerning technological innovation can be transferred to other types of innovation, e.g., to business model innovation.

Motivated by prior research, which showed that a shared usage of energy storage would have strong benefits (Parra, Gillott, Norman, & Walker, 2015), Essay 3 analyzed demonstration projects and contributed to the literature with two derived models for sharing electricity storage. It also showed how current regulations favor the inefficient use of electricity storage. The results underline the need to change regulation regarding the use of district networks for storage. The findings also support the theoretical work of Parag and Sovacool (2016) by showing specific examples of new business models in the district grid.

Essay 4 measured the evolution of the digital economy over time and as a country comparison, using a reproducible and comparable approach. The results show the differences between countries in the digital economy. The study shows that firms from the United States mainly govern the recent emergence of the digital economy. They highlight the need for policy action to enhance the performance of the German and European Innovation system.

Essay 5 showed that data-driven business models require new approaches for consumer protection. It demonstrated that there are increasingly more business models that use the data of end consumers as payment for services.

3.2. Implications

The presented findings of the essays have several implications. As predicted at the time of publication of Essay 1, costs of lithium-ion battery cells have indeed come down in the meantime. While the lithium-ion technology has played a major role in consumer electronics for more than a decade, it is now increasingly more likely that it will also find applications in electricity storage, where the techno-economical parameters have prohibited, until very recently, a broader use. This is also supported by recent studies, which found and have predicted further cost reductions (Kittner, Lill, & Kammen, 2017; Schmidt, Hawkes, Gambhir, & Staffell, 2017). Next to the field of renewable energy, the results of Essay 1 have therefore serious implications for the car industry and related policy making. Lithium batteries are not only interesting for stationary energy storage, but it continues to emerge as the leading technological option for electric vehicles. While the original argument of CO_2 reductions of electric vehicles can be debated in electricity systems with a high share of fossil fuel-driven plants, the recent discussion on NO_x related to air quality problems within cities (Anenberg et al., 2017) will likely further accelerate the diffusion of electric vehicles based on the technology. As batteries constitute a significant part of the value creation of electric vehicles, the findings on lithium-ion batteries should alert European policy makers. It remains to be analyzed why global markets invest in lithium-ion batteries, but many established car makers are not yet entering into battery production, even though the car industry is one of the key sectors in several countries such as Germany. This is particularly relevant in the context of the recent discussion and intentions to ban internal combustion engines entirely (Falck, Ebnet, Koenen, Dieler, & Wackerbauer, 2017). These developments raise important questions with respect to maintaining the competitiveness of selected countries.

There are several implications from the findings of Essay 2. First, since it shows that the knowledge network has differential effects on different types of innovation, firms could take into consideration what types of innovation could support the growth of their most important market segments, and consequently aim at adjusting their firms' knowledge structure accordingly. Policy makers designing different types of measures to support innovation also need to keep the findings in mind.

Along with the studies mentioned in Essay 3, Green and Staffell (2017) recently found several disadvantages of the increase of individual self-consumption without consideration of system effects. This also highlights the necessity to pave the way for the implementation of models developed and investigated in Essay 3. As the introduction of energy storage is, apart from pumped hydro, at a very early stage, a careful evaluation of scenarios and options is essential. As current decisions will impact the energy system for decades to come and bear the risk of lock-in to suboptimal solutions, a careful evaluation is crucial. The findings for the case of distributed energy storage are also in accordance with other studies calling for a broad and profound reform of the energy sector (Pérez-Arriaga, Jenkins, & Batlle, 2017). By giving a specific example for the case of energy storage, the findings reinforce the call of earlier research (e.g., Ruester, Schwenen, Batlle, & Pérez-Arriaga, 2014) for improvements in the regulation of the distribution grid to allow innovative business models.

Facilitating regulations would also be essential to reap all potential benefits of a transformation towards the “Energy Internet” (Zhou, Yang, & Shao, 2016). Rifkin (2014) introduced the concept as development once renewable energies reach zero marginal costs. With an abundance of renewable electricity after the expiration of the feed-in tariffs, concepts such as the investigated cases and peer-to-peer models (Parag & Sovacool, 2016), as well as yet-to-be developed concepts, will likely become much more widespread. This will, however, only be the case if policy makers adjust the regulatory framework to allow such models.

The findings of Essay 4 imply that the largest firms in the digital economy—with only very few exceptions—are American. While this is a significant finding for innovation and industrial policy, it also has important implications for other areas. It implies that regulation of these firms, for example concerning data protection and security considerations, has to find ways to govern these areas despite the fact that many of these businesses do not have significant physical assets in the country of operation. Also, the issue of base erosion and profit shifting (BEPS) is even more important for countries from which not many digital economy firms come. In this context, it will be particularly important to find ways to regulate large international players without unnecessarily reducing the potential for local innovation. In fact, trying to make policy based on the notion of controlling large, foreign, digital firms might have the effect that in the end, local start-ups are failing due to a competitive disadvantage, reinforcing the initial situation of the dominance of foreign firms. The observation that end-consumer access of a large fraction of the population of a given country (such as Germany) is only maintained by foreign firms should alarm policy makers, particularly as firms of the digital economy often have the option to shift their profits to jurisdictions with reduced or no tax rates (OECD, 2015a). This has led to recent proposals calling for radical change in the determination of taxation of firms in the digital economy, for example, by switching from a taxation of earnings to a taxation of revenues (Hirst, 2017).

Essay 5 highlighted that there is limited awareness among consumers regarding the value of data. This could also be due to a limited understanding of data-driven business models as a whole. Increasing transparency and the ability of consumers to decide between different offerings would boost competition and thus innovation.

The essays also show that the areas of energy and digital economy are increasingly merging; as a result, the boundaries between the sectors are blurring. Cloud-like business models are entering the energy sector, for example, for energy storage. Data-driven business models such as Nest are offering balance services. At the same time, digital business models such as sharing are applied to the transportation sector. Data companies are trying to use measurement and control for demand response.

3.3. Future research

There are numerous areas for future research resulting out of the presented essays. Future research could look more closely in the promising sub-technologies of lithium-ion batteries based on the findings of Essay 1. Also, the implications for the European automotive industry should be investigated in more detail, as the results of Essay 1 showing the dominance in lithium battery cell innovation of Asian manufacturers could mean serious value-creation shifts if electric vehicles continue to diffuse. This is particularly likely in the context of the recent revelations on diesel cars, which will likely trigger regulatory action.

There is also the possibility for future research following Essay 2. As it has been shown that the knowledge network has strong effects on the innovativeness, it would be interesting to see whether it is possible to extend the findings to the evaluation of potential M&As. For example, it would be interesting to see whether changes in the knowledge networks resulting out of

M&As have the same effects as changes caused by organic growth or shrinkage. Similar to research which has looked at inventor networks of single firms (Brennecke & Rank, 2017; Wang, Rodan, Fruin, & Xu, 2014), it would be interesting to also include the inventor network in a panel study based on multiple firms.

While Essay 3 revealed the barriers imposed by the regulation, more research is needed to ascertain how they could be removed to allow the efficient use of energy storage systems. Also, further research regarding how shared ownership schemes, such as cooperatives, could be implemented should be undertaken. These approaches should also be compared regarding cost effectiveness and energy efficiency, with opposite approaches of pooling small residential storage systems.

With respect to Essay 4, the research could be extended to privately held firms, to determine whether the finding of varying strengths can also be seen in this sample. Furthermore, differences in the propensity to initial public offerings (IPOs) could be determined, as well. As the analysis revealed significant differences in growth rates, more quantitative research would be needed to investigate the role of different factors to the regional and national innovation systems.

As a continuation of the conclusions in Essay 5, that consumers pay increasingly with their data rather than with money, more research is needed on how firms could also be directed towards offering the option to use services for a fee rather than asking consumers to reveal their data. Second, more empirical research is needed on the perception of the value of data by end-users.

The merging of the energy sector and the digital economy will progress. This will open numerous interesting avenues for research. Among those will be peer-to-peer concepts (Parag & Sovacool, 2016), for example, for local trading of electricity within communities. Such models will also be a promising arena for blockchain approaches. At the same time, the transportation sector will likely see a strong uptake of electric vehicles and an increasing influence of digital technologies. Further research should analyze which of the possible applications should be facilitated by policy makers to ensure that the digital transformation can contribute to sustainability.

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