How deployment policies affect innovation in complementary technologies—evidence from the German energy transition

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Abstract

The transition in the electricity sector has entered a new phase, in which the complementary interplay of different technologies is key for the future functioning of the sector. A key question in this regard is how deployment policies for clean technologies such as wind and solar PV affect innovation in complementary technologies such as battery storage. We present a qualitative study from the German power sector, in which we investigate the impact of the feed-in tariff for renewable energy generation, on two complementary technologies: consumer and grid connected battery systems. We find direct and indirect effects of the feed-in tariff. Indirect effects are primarily about positive expectations regarding the future progression of the transition. As deployment policies drive this progression, providers of complementary technologies interpret these changes as promising signals for their business. Direct effects differ for consumer and grid connected batteries. We find that innovation in consumer battery systems is disincentivized by some deployment policy features, while there are no such effects for grid connected batteries. When re-designing deployment policies for the next stage of the energy transition, it is important to take their effects on complementary technologies into account, or to develop specific policies targeting complementary innovation.

Key words

Clean technologies; deployment policies; complementarities; sustainability transition: grid integration; renewables

1. Introduction

The political consensus to mitigate climate change requires profound innovation in clean technologies such as wind and solar. To this end, numerous public policies that target the diffusion of clean technologies, so called deployment policies, have been implemented over the last decades (Hoppmann, 2015). In the power sector, deployment policies have been used worldwide in order to foster the diffusion of renewable energy technologies. In 2014, the International Energy Agency estimated an annual spend of around \$100bn[1] globally for renewable energy deployment policies in the power sector, projecting it to rise to \$175bn[1] in 2030 (IEA, 2014). Since these policies are largely financed publicly, they have received a lot of attention by researchers who investigated the effect of deployment policies on innovation and technology diffusion (del Río González, 2009; Jaffe et al., 2002; Kemp and Pontoglio, 2011).

However, clean technologies do not develop and diffuse in isolation, but require complementary technologies, services, business models, regulations and standards (Grubler, 2012; Haley, 2018; Markard and Hoffmann, 2016; Sandén and Hillman, 2011). In the following, we focus on complementary technologies, which we define as those technologies that increase the value of the focal clean technology and vice versa (cf. Grandori and Furnari, 2009). Examples of complementary technologies include electric vehicles and charging stations, or smart phones, apps and mobile communication networks.

In the power sector, there is an increasing need for complementary technologies such as energy storage, demand response or grid expansion to integrate substantial shares of variable renewables (Bird et al., 2013; IEA, 2017a; Sinsel et al., 2020). In California, where solar is approaching a 20% share in electricity generation, system operators face the challenge to provide fast ramping back-up capacity in the evening hours when the sun sets and demand is still high (Schwarz et al., 2019). In Germany, we see frequent curtailment of wind power generation in Northern regions because there is not enough transmission capacity to transport the energy to centers with high energy demand further South (Joos and Staffell, 2018). Similar challenges have been reported from Texas, Nova Scotia, the UK and Denmark (Bird et al., 2014; Haley, 2018; Strøm and Andersen, 2017).

These examples underline that interactions of multiple technologies become all the more important as the energy transition moves beyond early stages of development (Andersen and Markard, 2020; Markard, 2018). At a certain level of diffusion, the lack of complementary technologies can create bottlenecks (Markard and Hoffmann, 2016) or structural tensions (Haley, 2018) that impede further diffusion of clean technologies and have a negative impact on the overall performance of the sector.

While we know a lot about the effects of deployment policies on clean technologies, far less attention has been paid to the impact of clean technology deployment policies on innovation in complementary technologies (Hoppmann, 2015; Malerba, 2009). To better understand these effects, exploratory studies on a firm-level are very important since firms are in many cases direct respondents to deployment policies (Hendry and Harborne, 2011; Hoppmann et al., 2013). Meyer and Winebrake (2009) show that the increased diffusion of clean technologies spurs diffusion of complementary technologies by mutually increasing the economic attractiveness of clean and complementary technology. However, Hoppmann et al. (2014b) find that deployment policies may

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[1] Measured in 2013 dollars.

also negatively influence the economic viability of complementary technologies. As deployment policies shield clean technologies and raise their profitability, they lower the need to invest in complementary technologies. Since the existing literature provides mixed evidence as to the effect of clean technology deployment policies on complementary technologies, we aim to obtain a better understanding of the following research question: *How do deployment policies for clean technologies affect innovation in complementary technologies*?

To address this research question, we take a firm-level perspective and draw upon cases from the ongoing transformation of the power sector in Germany. More precisely, we investigate the impact of the feed-in tariff, which, among other technologies, supports variable renewable energy technologies (VRE), namely solar photovoltaics and wind power, on innovation activities in two battery storage technologies, consumer and grid connected battery systems, as complementary technologies. We focus on VRE due to their continuous growth over the past decades, largely fueled by deployment policies (Jacobsson and Lauber, 2006; Taylor, 2008). The choice for battery storage technologies as complementary technologies is motivated by their large potential for solving challenges associated with the integration of VRE (Malhotra et al., 2016; Sinsel et al., 2020). Due to Germany's ambitious renewable targets and the existing industry base for both renewable energy and battery storage technologies, we selected this country as an illustrative case for our analysis. We follow an inductive research approach and derive suggestions based on the analysis of archival data as well as 24 semi-structured interviews from firm representatives and sector experts.

This paper is structured as follows: In Section 2, we review the literature with regards to the gaps previously identified and build our initial research framework. In Sections 3 and 4, we introduce the research case and illustrate the methodological approach of our study respectively. Section 5 summarizes the results of our study, while Section 6 discusses the implications for literature, the limitations as well as areas for future research. Section 7 concludes by summarizing the study's main contributions and outlining the implications for policy makers.

2. Theoretical background

2.1 Deployment policy influence on innovation

Despite ambiguity regarding the relative effectiveness of specific deployment policy instruments, there is a largely-established consensus that deployment policies induce innovation beyond the diffusion of clean technologies (Grubler et al., 2012). Deployment policies have been shown to increase patenting activity (Calel and Dechezlepretre, 2016; Johnstone et al., 2010) and positively impact both product and process innovations (Cleff and Rennings, 1999) of clean technologies. In addition to localized effects on the clean technology value chain, scholars have shown positive geographical and sectoral spillovers from deployment policies (Peters et al., 2012; Stephan et al., 2017). Deployment policies have also been identified as an important element in supporting sustainable transitions of industries and sectors. To this end, deployment policies create protected niches for clean technologies (Hoogma et al. 2002; Kemp et al., 1998; Smith and Raven, 2012) and support market formation and legitimacy creation (Bergek et al., 2008; Markard et al., 2016), both of which have positive effects on innovation. To account for the wider effects of deployment policies, we define innovation within the scope of this study as investments in research, development and demonstration projects, products that are about to be commercialized as well as commercialized products. We focus on these stages in the innovation process since the crucial interaction of clean technology and complementary technology mainly takes place in the diffusion phase of the focal clean technology.

To investigate the effect of deployment policies on complementary technologies, it is important to discern which feature of a specific policy primarily accounts for the innovation effect. On the one hand, there is the chosen policy instrument – e.g. market-based instruments as opposed to standard-setting or command-and-control policies – that influence the type and the extent of innovation (Jaffe et al., 2002; Requate, 2005). On the other hand, policy design features such as a policy's incentive level, its predictability or its flexibility can be seen as catalysts for innovation (Kemp and Pontoglio, 2011; Vollebergh, 2007). Specifically, the latter approach has received increasing attention from scholars who aim to analyze the effectiveness of policy combinations, often referred to as policy mixes, since the concept of design features offers a tangible way to compare policies (Jenner et al., 2013; Rogge and Reichardt, 2016; Schmidt and Sewerin, 2018).

2.2 Firm-level analyses of deployment policy effects

In comparison to the literature that investigates innovation effects of deployment policies on an aggregate level, e.g. countries or sectors, studies that investigate mechanisms or causal relationships leading to innovation on a disaggregated level, e.g. firms, are relatively scarce. However, taking a firm perspective is important since firms are decisive actors as they react to policies. At the same time, firm-level analyses can provide early indications of developments measured on an aggregate level at a later stage, such as the diffusion of a certain technology. Lastly, firm-level analysis can uncover mechanisms that may not be apparent in studies at more aggregate levels of analysis. While taking a firm-level perspective is important for the above-stated reasons, firm-level analyses only provide indirect answers to questions regarding technological innovation on a system level. Therefore, instead of measuring innovation, we focus on describing innovation activities, i.e. the objectives of the innovation strategies of firms for specific technologies, and make conclusions on an aggregate level based on the interpretation of these activities.

Previous studies that describe innovation on a firm level provide a selection of important mechanisms through which deployment policies could affect complementary technologies. In their study on firm innovation as a reaction to deployment policies, Hoppmann et al. (2013) identify increased investor interest and improved access to capital as enablers for firms to pursue exploratory innovation activities. In a similar vein, firm-level studies can deliver insights on attributes that determine firm reactions to changes in their environment. One example for such attributes is specific technology characteristics. In their study on the evolution of the wind turbine industry in leading wind markets, Hendry and Harborne (2011) identify the respective technology life cycle stage as an important determinant for technological learning on a firm level. More specifically, they find that learning by doing and learning by using have led to faster innovation progress in nascent stages of the wind industry, while knowledge generated through formal research and development (R&D) activities has gained importance at later stages of the industry. These results, in turn, have implications on the type of policy measures which should be implemented at the relevant life cycle stage.

Despite the considerable amount of research on aspects of both policy impact and innovation outcome, studies have predominantly focused on investigating the effect of policies on specific clean technologies, while neglecting their effect on other technologies and firms that employ such technologies (Hoppmann, 2015). This issue particularly applies to complementary technologies in spite of their important role for the transition of socio-technical systems (Kemp and Volpi, 2008; Saviotti, 2005). While Hoppmann et al. (2013) provide detailed accounts of the mechanisms of policy effects on the firm level, it is unclear whether there are similarities in these mechanisms for innovation activities in complementary technologies.

2.3 Importance of complementary technologies for transitions

Complementarities are a central concept in systemic approaches to innovation. The general idea is to capture positive feedbacks between different kinds of elements. Complementarities are not confined to technologies. In organizational studies, for example, scholars have pointed to the importance of complementary assets (Tripsas, 1997) or complementarities between different organizations (Adner and Kapoor, 2010). In the following, we focus on complementary technologies, which we define as those technologies that increase the value of the focal clean technology and vice versa (cf. Grandori and Furnari, 2009).

Complementary technologies have been studied in different fields, including the literature on technology dynamics (Pistorius and Utterback, 1997; Sandén and Hillman, 2011), standardization (Cusumano et al., 1992; van den Ende et al., 2012) and various system approaches to innovation such as large technical systems (Davies, 1996; Hughes, 1987), development blocks (Dahmén, 1988) or technological innovation systems (Bergek et al., 2015, 2008; Haley, 2018). From a sustainability transitions perspective (Köhler et al., 2019), complementarities are particularly important as they direct attention to the interplay of different technologies at the sector, or system, level. As a system such as energy transforms, these complementarities are disrupted and new ones need to emerge. Such transformation processes may cause frictions and setbacks, which have been referred to as reverse salients (Hughes, 1987), structural tensions (Dahmén, 1988; Haley, 2018) or bottlenecks (Markard and Hoffmann, 2016) in the literature.

When investigating the role of complementarities and complementary technologies for sustainability transitions, Markard and Hoffmann (2016) propose three characteristics that help to better describe complementary relationships. One characteristic is the complementarity level, where they distinguish technology and sector level. While 'technology level complementarity' captures the (complementarity) benefits for a selected focal technology, 'sector level complementarity' is about performance of the entire sector, i.e. whether the clean technology and the complementary technology together "better contribute to fulfilling the societal function of the sector than each component on its own" (ibid., p. 66). In the case of photovoltaics and battery technology, consumer connected battery storage is primarily[2] a technology level complementarity to optimize self-consumption, while grid connected battery storage is a sector level complementarity relevant for PV system integration (Schwarz et al., 2019).

A second characteristic is the complementary relationship between two technologies, which can be bidirectional or unidirectional (cf. Pistorius and Utterback, 1997; Sandén and Hillman, 2011). This means that either both technologies mutually support each other's growth (bidirectional), or that growth in only one technology leads to growth in the other but not the opposite (unidirectional). Lastly, the complementary relationship between two technologies can be dynamic, i.e. it may change over time. Such change may also be absolute when a complementary relationship ceases to exist, or relative when one of the above-mentioned characteristics changes. To date, the literature on complementarities helps to better understand the different types and the context of complementary relationships. This literature, however, does not provide significant detail regarding innovation in complementary technologies, nor does it provide empirical insights on the policy influence on innovation.

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[2] See section 3.3 for further details.

3. Research case

3.1 *Rationale for case selection*

To analyze the impact of deployment policies on innovation activities in complementary technologies on a sector and technology level, the research case should fulfill three characteristics. First, we require clean technologies that have experienced strong deployment policy support over a longer period of time. Existing market diffusion is thereby important to verify the effectiveness of the existing deployment policies as well as, ensure that the degree of market diffusion is sufficient to generate a need for sector-level complementary technologies. Second, the chosen clean technologies should be significantly different from the existing, incumbent technologies in the sector. In this way, it is ensured that emergent complementary technologies feature a high degree of innovation activities. Third, the chosen complementary technologies should be complementary on a sector and on a technology level, and should both have reached a basic level of market diffusion. By differentiating complementarity characteristics we can verify whether deployment policies have a general or a differentiated impact on complementary technologies. A basic level of market diffusion ensures that observed differences in innovation activities are not due to a differing level of market diffusion between both technologies. We chose technologies in the German power sector as our research case because this setup fulfills all three case selection requirements (discussed in detail in the following sections). More specifically, we investigate variable renewable energies (VRE) such as wind power and solar photovoltaics (PV), and both consumer and grid connected battery storage as complementary technologies. Note that the chosen case is not only theoretically interesting, but also of high relevance for current public policy debates in Germany and other countries (Bird et al., 2013; IRENA, 2018). Also note that, in Germany, there were not only deployment policies for renewables but also for consumer battery storage. However, support for the latter was rather weak so that the effects of renewable energy deployment policies were dominant. See section 5.3 for further details.

3.2 *Clean technologies with strong deployment policy support*

Power generation from VRE has been identified as a major lever to reduce greenhouse gas emissions in the power sector. Therefore, these technologies have experienced significant policy support in Germany as well as worldwide over the last decades (Saidur et al., 2010; Solangi et al., 2011). The central deployment policy instrument in Germany is the renewable energy law. It was first enacted in 1991 as "Stromeinspeisungsgesetz" and, from 2000 onwards, it became the renewable energy law. This policy has been modified repeatedly over the following years (Hoppmann et al., 2014a), but its main mechanism remained unchanged until 2017[3]. The feed-in tariff has been acknowledged to be highly effective for supporting the diffusion of VRE (Couture and Gagnon, 2010; IRENA, 2015). The scheme targets renewable electricity generation (not complementary storage technologies) but it has some paragraphs, which set conditions under which storage technologies are exempted from feed-in cost allocation. In other words, we can expect some direct effects of this deployment policy on (consumer connected) complementary storage.

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[3] In 2017, the German government changed the law from a feed-in tariff to a tendering scheme (BMWi, 2017). The effects of this change, however, were still very much unclear when we conducted our interviews in 2017 and 2018.

Especially PV is said to have benefitted tremendously from the feed-in tariff scheme by establishing an increasingly efficient value chain which has significantly lowered the cost of power produced from this renewable energy technology. Due to this steep cost decrease, policy makers decided to sharply cut remuneration for PV in 2014, which has led to a lower diffusion in the following years (IRENA, 2015). This becomes evident from the development of the cumulative capacity (see Figure 1).

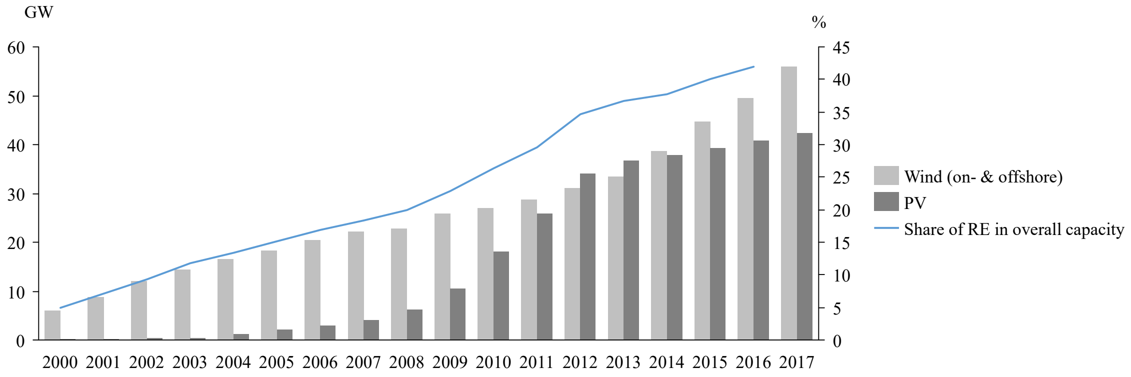

Fig. 1. *Cumulative capacity for wind and PV in Germany incl. share in overall generation capacity* (BMWi, 2018; EUROSTAT, 2018).

3.3 Significant difference between clean technologies and incumbent technologies

Both PV and wind generation technologies have a strong impact on the power sector since they differ in various aspects related to incumbent power generation technologies (Mueller et al., 2014). These differences create technical challenges in the power sector, such as grid congestion or increasingly volatile power infeed (Sinsel et al., 2020). An example that illustrates these challenges is the increase of redispatch activities, i.e. a forced curtailment of power production for reliability and grid congestion reasons which has increased drastically over the last years due to the infeed from VRE (cf. Fig. 2). While the amount of curtailed energy is still well below 1% of the annual electricity demand of Germany, the cost of these measures amount to €1.4bn in 2017 (Bundesnetzagentur, 2018a) that needs to be paid by end customers. These circumstances provide market opportunities for complementary technologies to provide new products and services to alleviate emerging challenges.

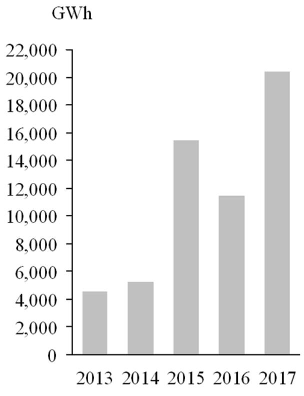

Fig. 2. *Redispatch of German transmission system operators* (Bundesnetzagentur, 2018b).

3.4 Technologies with different complementarity levels

In general, battery storage is highly complementary to VRE because it can store surplus energy in times of low demand and release it later when demand is high (Kassakian and Schmalensee, 2011; Sinsel et al., 2020). There are two business fields, which differ in the size of the installations, key performance parameters, the targeted customers and the level of complementarity. The first, grid connected battery storage, is complementary on a sector level, while the second, consumer connected battery storage, is complementary on a technology level. Grid connected battery storage units are designated to supply balancing power to the grid. As such, these units are used to balance the increasingly variable power supply at higher VRE shares. During operation, these installations are required to provide a constant amount of power to support grid reliability. Therefore, the installed power (see Figure 2; in MW) is the determining factor of such installations. In order to be effective on a transmission grid level, they are installed on a Megawatt scale. The average installation in Germany is around 7 MW in size.

Consumer connected battery storage units are installed on the premises of residential, industrial or commercial end-customers with local VRE generation. The purpose of these installations is to increase the self-consumption of the VRE generator on site; in Germany, this is mostly the case for PV plants. In doing so, the battery stores excess energy at times of high production, e.g. at midday, and discharges in the evening or night hours when there is low or no PV power generation. The main design parameter of these installations is energy (see Figure 2, in MWh) and since the size of these installations is correlated to the capacity of the VRE source, they are by levels of magnitude smaller than grid connected installations. The average capacity of consumer connected storage in Germany is around 8 kWh. Since the purpose of consumer connected battery storage is to lower electricity cost, it is complementary to VRE on a technology level. However, in order to improve the economic viability of consumer connected batteries, there is an increasing tendency to aggregate a larger number of these small scale units in order to provide balancing power for the grid when needed. In this case, they can switch their mode of operation and they can either be complementary on a technology level or on a sector level.

Despite the fact that German power system scenarios project that sector level storage technologies are not required before VRE generation shares are above 40 to 60% (Fürstenwerth et al., 2014), public and private R&D expenses for energy storage in Germany have risen significantly over the last decade. Data from the IEA (2017b) show an average annual increase of approximately 43% p.a. from $5m p.a. in 2007[2] to $174m p.a. in 2017[4]. It is important to note though that innovation in battery technology is largely driven by developments in electric mobility and portable electronics, i.e. outside of the electricity sector (see section 5.3). Both storage technologies show increasing diffusion levels. Figure 2 provides an overview of the cumulative capacity of both complementary technologies.

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[4] Measured in 2017 USD.

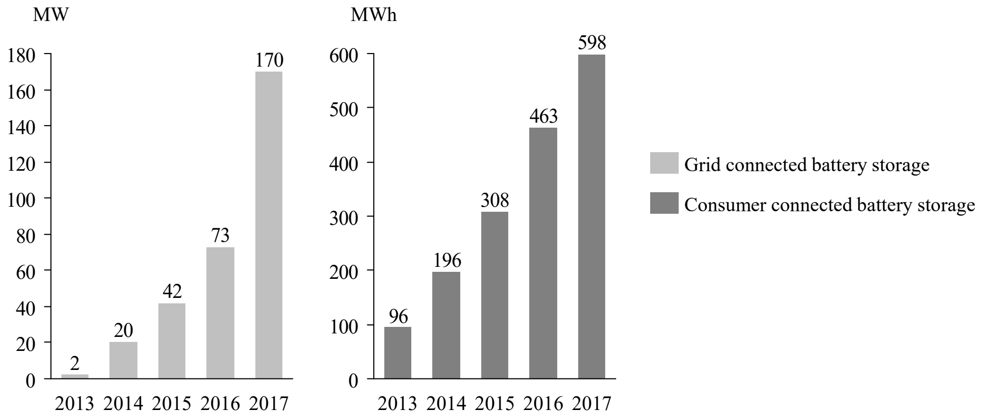

Fig. 3. *Cumulative capacity of consumer and grid connected battery storage in Germany* (DoE, 2018; Figgener et al., 2018).

4. Method and Sampling

To better understand the mechanisms that link deployment policies for clean technologies and innovation activities in complementary technologies, we conducted an in-depth qualitative case study based on archival data and interviews (Eisenhardt, 1989; Yin, 2018). This method enables us to reach the required analytical depth and to combine different sources of data for triangulation. Our analysis proceeded in three steps: First, we screened and analyzed articles from the German industry magazine 'Energie & Management' (E&M) to find out more on current industry and policy trends, the relevant firms active in both complementary technologies and statements that link clean technology deployment policies to the development of the storage technologies. In total, we screened 193 articles published between January 2011 and August 2018[5]. Subsequently, we analyzed 67 articles in detail, which provided an overview of the field as well as initial findings that we included in our results. Table A1 in Appendix A lists the articles we quote in this study (quotes marked by the letter D). The use of archival data in our case study increased the internal validity of our results, as it allowed us to triangulate the information we received, and reduced the risk of retrospective sense making on the part of the interviewees (Wolff, 2004).

Second, we conducted an initial series of interviews with industry experts to explore the general relevance of complementarities. We chose experts from a wide range of backgrounds, including members of industry associations, market analysts and plant operators (Table 1). This sample also included five experts from outside of Germany as well as operators of other complementary technologies to ensure a broad understanding of our phenomenon. The interviews were conducted between March and September of 2017.

Table 1
Overview of experts in the first round of interviews.

Category	Person	Stakeholder	Role
Industry association	E 01	German storage association	Senior expert for politics and regulatory affairs
	E 02	European demand response association	Expert for regulatory affairs
	E 03	Irish renewable energy association	Expert for regulatory affairs
	E 04	German storage association	Executive director
Complementary technology provider / operator	E 05	German demand response provider	Operations manager Germany
	E 06	Irish demand response provider	Operations manager Ireland and UK
	E 07	Transmission system operator	Head of innovation
	E 08	German virtual power plant operator	Head of marketing
	E 09	Pumped storage hydro technology provider	Head of innovation
Market analyst/Consultancy	E 10	Energy sector consultancy	Senior consultant
	E 11	Energy sector association	Expert for renewable intergration

Third, from October 2017 until November 2018, we conducted a second round of 13 semi-structured interviews with senior managers from firms that provide or operate consumer or grid connected battery storage solutions (see Table 2 for an overview of the sample). These interviews focused on the effects of deployment policies on innovation in the two selected complementary technologies. We deemed firm representatives as highly suitable sources for describing these effects as 'their' firms are central actors for responding to deployment policies. For identifying relevant firms and individuals, we first used the information gathered in the previous two research steps and relied on snowball sampling for arranging consecutive interviews. In order to identify potential differences between technology-level and sector-level complementary technologies, we divided our sample into firms that are active in consumer connected battery storage and those active in grid connected battery storage. If

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[5] We used the following keywords for our search query: 'battery', 'storage' and 'policy'.

the company of the interviewee focused on both technologies, we conducted the interview in two parts to cover each complementary level separately.

Within the sample, we chose firms and interviewees that differ in three characteristics to increase the reliability of our findings: (1) we selected technology providers and utilities that operate storage solutions to account for potentially differing policy effects along the value chain, (2) we included firms of different sizes to reflect on potentially differing policy impact on large or small firms and (3) we covered individuals responsible for different functions to outweigh potential perception differences due to specific roles within the companies.

Prior to each interview, we scanned publicly available sources for information on the firm and, if available, on the interviewee. Based on these insights, we adapted our interview guideline as a basis for the interview (see Table B1 in Appendix B for a typical interview guide). Each interview typically lasted 45 to 60 minutes, and was recorded and subsequently fully transcribed. Central statements that are referenced in the results as they describe causal relationships between our independent variable (deployment policies) and our dependent variable (innovation activities) have been authorized by the interviewees. The period of interest for our interviews was the last five years, since significant capacity increases in battery storage technologies happened during that time (see Figure 2).

After each interview, we reviewed the interview transcript in detail and tagged statements referring to our research constructs, deployment policies and innovation activities, using the MaxQDA 12 analysis software. To reveal the links between the constructs of our emerging research framework as well as arrive at conclusions across both cases, we used pattern matching (Yin, 2018). Once we identified contradictory results, we first attempted to clarify our understanding with the interviewee through a follow-up discussion. If the results remained contradictory, we adapted our constructs or the research framework. In such cases, the updated research framework was used as a basis for the consecutive interviews. In this way, we refined the insights from our interviews until a saturation level for additional insights was reached (Eisenhardt, 1989).

Table 2

Overview of companies and interview partners in the second round of interviews.

Person	Stakeholder	Business domain	Role	Technology-level complementarity	Sector-level complementarity
I 01	Utility	Research & development	Senior manager	•	•
I 02	Utility	Business development/ Portfolio management	Senior manager		•
I 03	Technology provider	Regulatory affairs	Head		•
I 04	Technology provider	General management	CFO	•	
I 05	Technology provider	General management	CEO	•	•
I 06	Technology provider	Business development/ Portfolio management	Head	•	
I 07	Technology provider	Business development/ Portfolio management	Senior manager		•
I 08	Technology provider	Business development/ Portfolio management	Head	•	•
I 09	Utility	Asset management/ Operation	Senior manager		•
I 10	Technology provider	Research & development	Director	•	•
I 11	Utility	Business development/ Portfolio management	Senior manager		•
I 12	Technology provider	Strategy	Vice president	•	•
I 13	Utility	Business development/ Portfolio management	Senior manager	•	
				8/13	**10/13**

5. Results

Our main findings are as follows. (1) Deployment policies can have direct and indirect effects on innovation in complementary technologies. (2) Indirect effects are primarily about positive expectations regarding the future progression of the transition including changes in markets and regulations and the subsequent need for complementary technologies. (3) Direct effects differ for technology and sector level complementarities. We find that innovation in technology level complementarities is disincentivized by some deployment policy features, while there are no such effects for sector level complementarities. We detail these issues below, taking three steps. First, we characterize the innovation activities for the chosen cases and show that the differentiation between sector and technology level complementarities matters. Second, we illustrate the causal relationships between deployment policies and innovation activities in complementary technologies. Lastly, we reflect on alternative explanations for the differences in innovation activities.

5.1 Characterization of innovation activities

Our results show that firms pursue different innovation activities depending on their business field, i.e. whether they engage in grid connected storage or consumer connected storage technologies. See Table 3 for quotes that exemplify the innovation activities of the firms in our sample.

Firms active in grid connected storage focus on exploring new applications for their technologies – an approach which we refer to as *sectoral exploration*. Firms do so by engaging in public demonstration projects (I 02, I 03, E 09), by concluding alliances with other market participants in the sector (I 05, I 10) or by keeping technology interfaces open in order to remain flexible if new market opportunities arise in the future (I 10, I 12). The approach to pursue sectoral exploration is mostly explained with the relative uncertainty as to how the market, its customers as well as the performance requirements of both will develop. As the CEO of a battery storage provider and operator (I 05) put it: "*[W]e want to be prepared […] – be it technically or from an R&D point of view – to serve every market possible […] with our battery storage fleet*."

In contrast, firms active in consumer connected storage perceive a higher degree of certainty in their market environment and in the relevant performance requirements to be successful in the market. Therefore, they conduct only limited market exploration, focusing instead on *cost reduction* and *local integration*. While cost reduction is relevant for both business fields, it is a strategic priority for firms active in consumer connected storage (I 01, I 04, I 13, E 10). Firms dealing with grid connected storage achieve cost reductions indirectly, e.g. as they optimize their battery sourcing (I 01, I 03, E 04).

In the consumer connected storage business, we discovered various innovation activities aiming at cost reduction. One focus for firms active in consumer connected battery storage is the mission to bring *"standardized solutions to the market*" (D 01). When implementing standardized solutions, one area of cost reduction is the "*balance of system; [Company X], for example, has made a big announcement last year that they now have a modular system in place which one can install in only a few simple steps"* (E 10). The head of business development of a battery storage provider (I 06) defined their cost reduction efforts even broader: *"that you keep tweaking the hardware, that one can install the system more quickly, that the individual components* *get smaller and lighter. We also talk packaging and logistics – so how you really get the product to the customer."*

In addition to cost reduction, firms in consumer connected storage pursue innovation projects to better integrate with other technologies of their customers, an innovation activity we refer to as *local integration*. One interviewee saw *"integration [with other appliances behind the meter] as the main driver for innovation in the area of self-consumption optimization."* (I 08). The focus for integration remains on the existing customer base as opposed to firms with sector-level complementary technologies who look for new clients and partners within the whole sector to enhance their offerings.

Firms that are active in both business fields show all of the described activities simultaneously (I 01, I 10, I 12).

Table 3
Innovation activities by complementarity level

Complementarity level	**Innovation activity**	**Exemplary quote**	**Source**
Sectoral	Sectoral exploration	*[...] we [want] to keep our platform open and [...] not try to [...] provide everything with our system, but simply [offer] open interfaces. We do so because when I invest in our home storage today - this is an investment for 15 to 20 years. Who knows what will be in 10 years or how I can make money with such a device in five years.*	I 10
		[...] we often [realize] that we actually do not use a significant part of the flexibility of the batteries [...] and that there are capacities where [...] we [could] still do something else.	I 11
Technological	Cost reduction	*The third point is indeed cost. We constantly work to make [the system] more cost efficient in terms of sourcing and in terms of technology, mainly [to] save parts and [...] to standardize things.*	I 06
		Cost reduction and product experience [drive innovation]. This means simpler installation, a more compact, more appealing design. There were only few changes from the hardware point of view over the last years.	I 10
		A lot of innovation happens on the battery storage side. People say 'hey, I can get the system cheaper with the same components! Let's realize new functionalities'.	I 08
		[...] self-consumption optimization behind the meter is a market segment of the German energy storage industry , which will continue to grow over the next years. Yet, home storage systems as products are likely to become increasingly price sensitive as the market grows.	E 04
	Local integration	*[We strongly believe] that by collecting data also from the components of the system, we will be able to generate new business cases [within the homes] in the near future.*	I 13
		The first goal is to balance self-generation and demand for electricity on a cellular household level. This gives rise to additional opportunities, for example that electric vehicles can be better integrated, etc.	I 12
		Alliances in this area have not really materialized. What we are trying to integrate is the home energy management system.	I 13

5.2 Effects of deployment policies on complementary technologies

The differences in innovation activities can be explained by different effects of deployment policies on both complementary technologies. We identified two sets of mechanisms, direct and indirect. We speak of indirect mechanisms if innovation activities in complementary technologies are caused by the diffusion of the clean technology. In contrast, direct mechanisms are present if innovation activities in complementary technologies are caused by the sheer presence and features of clean technology deployment policies rather than the actual diffusion of the clean technology. Figure 3 illustrates both mechanisms.

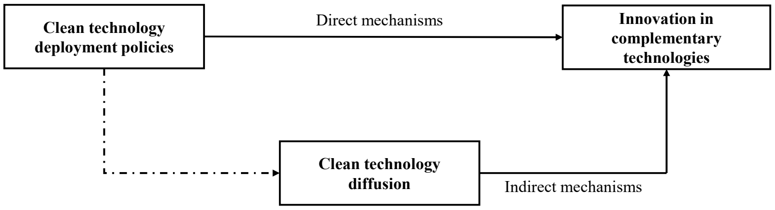

Fig. 4. *Research framework with indirect and direct mechanisms.*

5.2.1 Indirect mechanisms

The main indirect mechanism is about favorable *profitability expectations,* which positively influence innovation activities on both complementarity levels. Mechanisms, however, largely differ between the two complementarity levels (see Table 4 for an overview). First, firms active in grid connected storage presume that *"with the further expansion of renewables we assume a rising volatility of electricity prices in the long run. Then storage […] will get increasingly attractive"* (D 02). Deployment policies therefore appear to be indirectly responsible for the increasing future market potential of sector-level complementary technologies. The inevitability of large-scale storage installations constitutes a widely held belief over the last decade, as an E&M article stated in 2012: *"It is clear to everybody that Germany will need new, large power storage devices if the share of renewables should increase to 50 percent or beyond"* (D 02). Despite the certainty of the future need for more flexible technologies, firms are aware that *"there is a whole set of flexibility options which should […] compete against each other"* (E 09).

At the same time, firms remain uncertain about the regulatory measures that could be implemented in the future, as the CTO of a German utility in an E&M article emphasized in 2017: *"Nobody knows how many power plants will drop off the market and hence how profitable the balancing power market will be in the future, especially since policy remains to be erratic"* (D 03). We therefore conclude that there are two triggers of innovation activities for sector-level complementary technologies: First, firms presume *market changes* will arise through increasing volatility, creating relevant market opportunities. Second, if these opportunities do not arise through the market, firms presume that they will emerge through *regulatory changes* or policy measures (E 01, E 10). A senior portfolio manager of a utility summarized the two expectations in connection to innovation activities: *"Our rationale for our storage investments goes as follows: As the market share of renewable electricity sources grows, an increasing number of flexible thermal plants will become unprofitable and shut down. To maintain grid stability, the regulating authorities will have to provide incentives for investors to provide new, more sustainable sources of flexibility [...]. The future value of these flexibility sources lies either in increased price fluctuations [...] or additional revenue sources such as capacity payments. In both cases the value of sustainable flexibility is likely to increase."* (I 02).

Second, firms that are active in consumer connected batteries see deployment policies as a means to *expand their addressable market* since their respective business requires the local presence of a clean technology. The CEO of one battery storage provider (I 05) illuminated this point by stating that *"the one million or so households which have a PV plant are eventually the foundation on which we stand. […] If they weren't there [our business model] would not exist."* In contrast to the sector-level business, the functionalities and interfaces between VRE generation and the battery storage unit are largely defined at the technology level. Firms therefore innovate in close correspondence to deployment policies in order to ensure a stable economic viability for the existing application as opposed to looking for new revenue streams.

Despite the observed differences, we can summarize that the indirect mechanisms of deployment policies have a positive effect on innovation in complementary technologies both at the technology and sector level.

Table 4
Mechanisms through which deployment policies ***indirectly*** *affect innovation activities in complementary technologies.*

Complementarity level	**Mechanism**	**Exemplary quote**	**Source**
Sectoral	Profitability expectation through market changes	*So the reason why we built the first storage unit was for sure under the context of the renewables. [T]here will be less conventional power plants […] in the medium term [and] the typical market players will actually be gone. And then there are mainly other technologies [like storage].*	I 01
		[Our innovation strategy is based on] a few underlying assumptions. So one assumption is: The more fluctuating power I have in the grid, the more storage I need to balance it. One does not see it so clearly today, but we think this has to come.	I 05
		[...] the [policy] support for renewables has led to a higher share [of renewables], and the higher share of renewables has led to a higher need for storage or is in the process of doing so because of the […] difference between supply and demand, […] and the difficulty to forecast all of that. [...] Since storage will become more relevant, we concluded that we should look at batteries [...].	I 09
		In principle, we believe in flexibility in the energy market. I believe this is undisputable.	I 08
		I see a connection to the share [of renewables]- if that is beyond 40 to 50 percent, storage […] will undoubtedly play an increasing role [in the system].	E 08
		Without a doubt, storage contributes to balancing supply and demand. The higher the share of fluctuating generation from wind and solar, the higher the need for such balancing.	D 04
	Profitability expectation through regulatory changes	*[Our product strategy does not evolve] from renewable support alone, but rather from renewable support in connection with the state of the grid. So, in Germany […] we already have […] a very high share of renewables, especially variable renewables, which makes the grid less stable and therefore requires new technologies. But since we are integrated into the larger European grid, [...] renewable integration is not a real problem today. But politicians will only act to create a regulatory environment supportive of new technologies […] when they are forced to do so by external events of public pressure, e.g. the underground HVDC cables in Germany.*	I 03
		I firmly believe […] that if we need [new balancing power markets], new markets will be created. And hopefully they will be designed in a way so as to not discriminate storage.	I 11
		Business cases for operating energy storage systems can only successfully further develop and be integrated in the markets if the regulatory framework allows for so-called "multi-use models" with storage solutions. Like a swiss-army knife - one tool that can be applied in various ways - also a storage technology can be applied in many different ways, for example for reactive power services, black start capability, etc.. All of these functions are technologically possible but storage will only be integrated into the energy system if there is a market remuneration for the services it provides.	E 04
Technological	Profitability expectation through expanding the addressable market	*[…] we have about 1.5 million residential PV plants in Germany, but we cannot yet unlock that potential because the business case is not yet strong enough. But when it is, we will achieve a mass market for these systems.*	I 06
		Once customers own solar and storage, they become significantly more interested in other energy transition technologies as well. They start to have a far more sophisticated understanding of how electricity flows, where it comes from and at what prices. It is this interest of customers which in turn can drive additional innovation.	I 12
		The […] market for home storage systems […] has [mostly] evolved through [the increase in residential] PV, which was fostered by renewable policy support.	E 04

5.2.2 Direct mechanisms

When investigating direct mechanisms, we see a striking difference in the effects between the two complementarity levels (see Table 5). We start with technology level complementarities due to the prominence of the effects. We identified three mechanisms that generated disincentives for innovation in complementary technologies. These are related to the features of the deployment policy. (1) A high *degree of protection*, in the sense that the clean technology is very much shielded from market forces, does not work in favor of innovation activities in complementary technologies. In our case, firm representatives argued that the feed-in priority of VRE constitutes a disincentive for them to innovate since sales are guaranteed whether the power is needed or not. Without this guarantee, VRE operators will have to follow market signals, which would create a strong incentive for utilizing storage solutions (I 12, E 04). The head of business development of one battery storage provider (I 08) even said that: *"for the smaller private plants I would […] even claim that there will be more innovation if the EEG ceases to exist."*

Second, a high *incentive level*, i.e. in our case the level of the feed-in remuneration, can also have a negative impact on technology level complementary technologies since earnings from the feed-in remuneration currently constitute the benchmark for earnings generated through the use of a battery storage unit. This view is confirmed in one E&M article (D 06): *"Until now, the integration of a relatively expensive [battery] storage* *will negatively affect the profitability of a PV plant. Directly feeding power into the grid is currently still very attractive thanks to the [...] feed-in remuneration of the EEG."* A senior consultant (E 10) argued from the opposite perspective, but arrived at the same conclusion: *"the reduction of the feed-in tariff in Germany [was one of the main reasons] that residential storage could even get attractive."*

Finally, there might be *specific rules* of a deployment policy that disincentivize innovation activities since firms adapt their product portfolio according to these rules. One head of business development (I 08) illustrated this impact in reaction to a specification of the German feed-in tariff in 2014: *"In the past we had a slightly broader portfolio […]. But [some products] were not viable [any more] since [policy makers] decided to charge the EEG [cost] allocation on them. [T]his was for sure the reason why we decided to take these larger plants from our portfolio."* The above observations lead us to conclude that direct mechanisms of deployment policies may also have negative effects on innovation in complementary technologies on a technology level.

For grid connected batteries, interestingly and in contrast, our interviewees did not see any causal link between deployment policies and their innovation activities. The head of innovation of a pumped storage hydro technology provider (E 09), for example, confirms the absence *"of a direct link between renewable subsidies and storage. [I]t is rather indirect and has to do with the share [of renewables] and the merit order effect"*. This view is reiterated by a senior manager of a utility (I 09) who illustrates the difference between indirect and direct mechanisms: *"If the further expansion of PV leads to changes in grid codes and the remuneration of grid services, then there is an indirect link [between renewable energy policy and our product portfolio]. But not by somebody saying: 'There is this change in legislation – we should build a new power plant.' I don't buy this […]."* One way to explain that deployment policies have no direct effect on sector-level complementary technologies is the level of interaction between clean and complementary technology. In the case of sector-level complementary technologies, both types of technologies interact via the market as opposed to technology-level complementary technologies, where the interaction takes place directly through the owner of both technologies.

Table 5
Mechanisms through which deployment policies ***directly*** *affect innovation activities in complementary technologies.*

Complementarity level	Mechanism	Exemplary quote	Source
Sectoral	No effect	*[…] we believe that the EEG […] is not decisive for the further development in stationary battery systems any more.*	I 10
		[…] if the feed-in for PV would be reduced during the next years, […] this would not change the perspective [of our plants].	I 09
		The German control energy market is an example for a market in which energy storage solutions already participate. […] This market is particularly attractive for energy storage systems such as batteries, since they can provide power quickly and flexibly. And [this is a market in which] economic viability has nothing to do with any kind of subsidies.	E 04
		[…] specifically, the [support through the] EEG is not relevant for […] the battery business today.	I 11
Technological	Degree of protection	*If renewables get […] renumerated […] even if the power is not fed into the grid […] then there is zero incentive for generators […] to produce electricity based on the existing demand.*	E 01
		Currently, there are around 1.5 million residential PV generators that fall under EEG terms. Without the EEG's feed-in priority, these generators would run into problems. Once there is no feed-in priority any more, operators need to act according to market needs. They will need to adjust power feed-in and storage can help them with that.	E 04
		The owner of an installation facing the risk of curtailment will inevitably look into storage. Thinking rationally, [this owner] will rather store electricity than be curtailed.	I 12
	Incentive level of deployment policy	*Latest when the feed-in tariff will be phased out is from 2020 onwards, where optimizing self-consumption will increasingly be seen as a business case.*	D 02
		Looking at the current [low] level of the feed-in tariff, optimizing self-consumption frequently pays off, specifically for private households.	D 02
		[An expert] believes that in about seven years, when a large number of plants will fall out of the feed-in tariff scheme, there will be a boom in storage.	D 05
		Generally speaking, the [EEG] tariff structure has a large impact on [self-consumption].	I 01
		The delta between the feed-in tariff and the retail price of electricity needs to be so big that we can fit a storage device in there.	I 06
	Specific rules of deployment policy	*If [the residential PV plant] is below 10 kW or 10,000 kWh of production per year, then [we do not have to] pay the fee […]. [M]any who could build somewhere around this threshold consciously [decide] for a smaller plant then.*	I 10
		The EEG has this provision with the fee for self-consumed electricity. Now, we try to fall under the de-minimis rule since households typically consume less than 10,000 kilowatt hours […]	I 05
		The support policy, the design of the support policy, is a decisive factor […] in how things are solved behind the meter.	I 04

5.3 Rival explanations for differing innovation activities in complementary technologies

In the following, we reflect on three alternative explanations for differing innovation activities among complementary technologies. We briefly describe their impact and discuss why their presence does not impact the main results of our case study.

A possible rival explanation which could explain the differing innovation activities between complementary technologies on a sector and technology level could be innovations in adjacent sectors such as the IT and automobile sectors rather than the differing effect of deployment policies. Those sectors make up the majority of produced market quantities for battery modules which are the basic elements for storage units of both complementary technologies. Reductions in the cost of battery modules are indeed an underlying reason why this previously high-priced technology is increasingly seen as a viable alternative to other electricity storage technologies. A senior R&D manager of a utility (I 01), for example, confirms this view by stating: *"[A] larger factor which played a role for the cost decrease of storage is […] e-mobility […]."*

However, in our research setting, we argue that this circumstance does not affect the findings from our study for two reasons: First, since all firms that produce battery storage technologies in our sample source battery modules externally, innovation primarily occurs in other areas for these firms, as the business unit CEO of a stationary battery storage producer confirms: *"The value-add of stationary storage lies largely in the smart integration of the different components [of the unit] and their integration in the power generation and distribution system. The cells are not the decisive factor in this case."* (D 07). This means that all firms in our sample benefit from advances in battery module technology. The observed differences in innovation activities can therefore not be attributed to these developments. Second, power sector applications only constitute a small fraction of the overall battery market (Rechargebatteries, 2018). This makes it unlikely that the battery industry has a high focus on this market segment in terms of specific innovation requirements for the analyzed cases. Therefore, we do not see indications that the analyzed complementary technologies benefit differently from cost advantages passed on through the value chain.

Another rival factor that could be brought forward to explain the observed differences in innovation activities is related to market differences between the two complementary technologies. Indeed, both technologies differ in terms of their customers, output quantities and installation sizes (see section 3.4). In the case of consumer connected battery storage, for example, which is directly sold to private customers, we could imagine that marketing considerations, such as product experience and branding, influence the choice of innovation activities. While we acknowledge that these factors could have increasing importance in the future when battery technology enters into a mass market stage, we argue that they matter less for the early adopters, or lead users, we currently see in the market. A recent study (Engelken et al., 2018) as well as our interviewees confirm these motives. The head of business development of one provider for consumer connected battery storage (I 06), for example, states: *"To a certain extent the storage market is still [...] driven by first movers [...]. People start to understand that with PV they can save electricity cost. Once storage systems get an economic price point, this can further reduce electricity costs. This will be the start of the mass market."* In the area of grid connected battery storage, one operator (D 03) argues very similarly: *"If we [...] take the equipment cost and calculate the current remunerations on the balancing market against it [...], the storage is paid off within ten years. We will likely not earn big money with it but we have a show case project because green window dressing is not enough we need real plants"*.

A third rival explanation for the different observed innovation activities pertains to deployment policies, which directly target complementary technologies. While there is no deployment policy for grid connected battery storage for balancing power provision, there is an investment grant scheme for consumer-connected battery storage for self-consumption optimization. This could lead firms to focus their activities on cost efficiency rather than exploring new business opportunities. Our interviewees, however, did not confirm the significance of this subsidy for their innovation decisions but rather referred to the EEG as the main factor. Battery subsidies have been used for approximately one third of newly installed units, which shows that its effects are limited. The secretary general of the German storage association (E 04) confirms: *"[The] KfW program highlighted the governments' interest in supporting the growth of energy storage technologies. Yet, when one looks at the total share of supported installations, its impact was rather marginal."* Moreover, the interviewed firm representatives signaled a decreasing confidence in the scheme since policy makers have significantly tightened eligibility requirements over the last few years (I 12, I 13).

6. Discussion

Our study has shown that deployment policies can have both direct and indirect as well as positive and negative effects on innovation activities in complementary technologies. In the following, we present the contributions to the literature, reflect on the wider applicability of our findings and highlight the limitations of our analysis accompanied by avenues for future research.

Our study contributes to the literature in three ways. First, we add to the literature on sustainability transitions by studying an advanced phase of a transition, in which clean technologies have already diffused widely so that they affect the 'functioning' of the entire sector (Markard, 2018). In such an advanced transition stage, policy analyses cannot merely focus on specific technologies, but need to be widened to larger interactions of focal technologies (here: variable renewables) and complementary technologies (here: storage) and their repercussions for sector developments (Andersen and Markard, 2020; Geels, 2018; Markard and Hoffmann, 2016; Papachristos et al., 2013). As a consequence, it becomes relevant as to how policies in general, and deployment policies in particular, affect complementary technologies and sectoral change more broadly. Our results show that deployment policies need to be adapted over time to make sure that innovation in complementary technologies is stimulated as well. Our analysis also highlights that sector-level complementarities (here: grid connected batteries) play an increasing role in later transition stages, thereby pointing to the growing relevance of system changes.

Second, we extend the literature on deployment policies and policy mixes as we highlight the relevance of complementary technologies and broader effects at the sectoral level. We find that policy features such as a high degree of protection, a high incentive level or specific rules may impede innovation in complementary technologies, while indirect effects seem to stimulate innovation. In this light, future studies on the effectiveness of deployment policies (Kemp and Pontoglio, 2011; Newell et al., 1999) should therefore consider effects on complementary technologies. This also applies to the literature on policy mixes (Kern et al., 2019; Rogge and Reichardt, 2016) which, besides a few exceptions (Ossenbrink et al., 2018), tends to focus on single technologies .

Third, we contribute to the literature on complementarities and complementary technologies (Dahmén, 1988; Markard and Hoffmann, 2016; Sandén and Hillman, 2011). We find that businesses emerge around complementary technologies and that their innovation activities (and prospects) are driven by expectations around the future diffusion of the focal (clean) technology, which is in line with earlier research on the role of expectations for innovation (Borup et al., 2006; van Lente and Rip, 1998). At the same time, there may also be unintended policy effects if deployment policies 'overprotect' clean technologies. We also show that policy effects may differ for technology- and sector-level complementarities, which underlines the relevance of the earlier distinction of these two levels. These differences as well as, for example, temporal changes in complementary relationships, require further attention in order to identify potential bottlenecks as the transition progresses.

When reflecting on the applicability of our approach to other cases, we want to highlight two dimensions: different policy settings and different technologies or sectors. A comparable case with a different policy set up is the power sector in California. Despite different deployment policies, the diffusion of grid and consumer connected storage technologies exhibits similar patterns as Germany[6]. Similar to our study, we could therefore analyze the impact of these policies on grid and consumer connected storage as well as the underlying mechanisms. In contrast, a comparable case focused on a different technology is the mobility sector and the upcoming trend towards electric vehicles: With the increasing diffusion of electric vehicles, utilities and local grid operators project changing electricity use patterns and specifically higher demand peaks at times when the vehicles are to be charged (IRENA, 2019; Mwasilu et al., 2014; Richardson, 2013). On the one hand, higher peak demand in local grid areas can be addressed by reinforcing the grid infrastructure, i.e. through complementary technologies on a sectoral level. On the other hand, demand peaks could also be addressed on a technology level by implementing a communication interface between the electric vehicle and the grid operator to enable smart charging of vehicles. The described changes in power demand could even enable new business opportunities for car owners by offering their car as a temporary storage device on the power market (Mwasilu et al., 2014). Summing up, both examples highlight the wider applicability of our analysis. However, further research is required to determine whether and how the observed effects are transferable.

This brings us to the limitations of our study. First, it is an open question whether our findings are generalizable. The power sector itself is characterized by a very specific policy environment and a high degree of systemness, i.e. technologies, infrastructures and policies are interacting more intensely than in other sectors (Markard, 2011). Comparative studies may therefore seek to identify whether our conclusions remain valid in other sectors (and places). Second, our research does not involve private households, who are the predominant users of consumer connected battery storage. Although the technology providers we interviewed provided insights on how deployment policies affect the users of this technology, we cannot exclude the existence of further effects of deployment policies on household level adoption (Kubli et al., 2018) . Further research on adoption motives for these technologies could therefore help to ensure the validity of our results. In a similar vein, we also did not capture the perspective of battery producers. These operate internationally and serve much larger markets (e.g. electric mobility, portable electronics), which is why we assumed that they might find it difficult to assess the impacts of specific policies in a specific country. Fourth, we cannot make claims about the relative importance of the different effects. Many interview partners found it difficult to assess the relative influence and there was not enough room in the second interview campaign to explore this in detail. Another interview campaign or even a different format (e.g. workshop) would have been necessary to shed more light on this. Finally, our research uncovers differing effects of deployment policies on different complementary technologies. It seems therefore necessary to strike a balance between the support of clean technologies and complementary technologies. What such a balance might look like, e.g. the simultaneous support of clean and complementary technologies at both levels, or merely the support of specific complementary technologies, is, however, not answered with our study. We believe that such questions can be answered through comparative case studies in different jurisdictions.

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[6] By the end of 2017, roughly 80 MW of grid connected storage (DoE, 2018) and roughly 20 MWh of residential storage had been installed in California (Wood Mackenzie, 2018).

7. Conclusion

Our study investigates the impacts of deployment policies targeted at clean technologies on complementary technologies. For the case of battery technology in Germany, we find both positive and negatives effects. With the latter, we uncover a dilemma in which an effective deployment policy induces innovation in a clean technology, while potentially stalling innovation in complementary technologies at the technology level. The underlying mechanism is the following: If a deployment policy provides a strong (and intended) protection of a clean technology, this protection will reduce the need for complementary technologies, which might also (unintentionally) lead to a reduction of innovation in the complementary technology. At the same time, however, the deployment policy also creates positive expectations about future market developments, which again stimulate innovation. In other words, there are positive and negative effects and it comes down to the actual policy design features to determine which effects prevail.

With regards to policy making, we see the following implications: First, we show that when devising policy measures, policy makers do not only make conscious decisions about the technologies they aim to support, but they also, whether consciously or unconsciously, influence the development of complementary technologies. A strong deployment policy can therefore create a favorable environment for clean technologies yet impede innovation in specific complementary technologies. This increases the risk of bottlenecks or undesired lock-ins of complementary technologies, which may result in diminished technical, economic or environmental performance compared to their peers and therefore reduce efficiency of the overall socio-technical system (Markard and Hoffmann, 2016; Schmidt et al., 2016). Overall, the challenge of systems thinking is therefore highly important when devising policy interventions in times when clean technology deployment is advancing (McMeekin et al., 2019). Two ways to design more systemic policies could be to (1) enlarge the policy making scope beyond specific clean technologies while addressing the performance of the larger sector or the transition itself or (2) introduce a policy succession in which clean technologies are supported first while shifting support to complementary policies at a later time.

Second, on the level of single policies, the central question that arises from our analysis is as follows: Can the negative effect of existing deployment policies be neutralized by changing these policies? One option to accomplish this would be to widen the policy objective of the deployment policy to account for the progress of both clean and complementary technologies as opposed to only focusing on clean technology development. While this seems to present a viable solution, the general incompatibility of objectives might remain or further unintended spillover effects could be overlooked. Another option would be to continuously reduce the strength of deployment policies. While an adequate balance between clean technology and complementary technology support is necessary, a policy down-scaling seems a difficult endeavor since it might stall the diffusion of clean technologies only to reduce negative impacts on complementary technologies. A third option would be to introduce ‘compensatory’ measures for complementary technologies against the negative effects of deployment policies for clean technologies. While the introduction of additional deployment policies may be difficult to achieve, it seems, however, the most straightforward way to cope with the identified negative effects on specific complementary technologies. Such new combinations of deployment policies for clean and complementary technologies can contribute to a new understanding of policy mixes for sustainability transitions (Kern et al., 2019).

8. Appendix

Appendix A: Overview of quoted archival documents

See Table A 1.

Table A 1
Overview of quoted archival documents

Document	Title	Date
D 01	"Energy Flexibility" – the E&M manor house talk	October 27, 2015
D 02	Smart system operation with storage	March 8, 2018
D 03	One battery, please	February 17, 2017
D 04	Storage in power markets – privileged or unreasonably charged?	September 5, 2017
D 05	R&D – storage in question	November 20, 2013
D 06	Batteries as profit generators	April 24, 2013
D 07	Value add through intelligence	February 20, 2015

Appendix B: Typical interview guide

See Table B 1.

Table B 2
Typical interview guide used for the expert interviews

Category	Exemplary questions
Innovation activities	What kind of innovation actvities did you pursue during the past years?
	Did you pursue demonstration projects during the past years?What are your current plans for the coming
	Did you launch/commission new products/solutions? Do you plan to launch/acquire new products/solutions in the next years?
	In which areas of your products/solutions do you pursue innovation activities?
	What are the targets of these innovation activities?
	Did your innovation activities change over time or due to certain events? If yes, why?
Role of deployment policies for innovation activities	What determines your innovation activities?
	What role does policy play for your business in general and for your innovation activities in specific?
Link between deployment policies and innocation activities	How does the market growth for renewables affect your innovation activities?
	Where do these effects materialize in your business? In the revenue/profit of your firm, in monetary or other input resources?
	How does the support policy for renewable affect your innovation activities?
	Which aspects or characteristics of the renewable support policy have an impact on your innovation activities?
	Did the influence of the support policy for renewables change over time?
	How did you change your innovation activities when the policy support changed?
	When the policy support for renewables would be decreased - which innovation activities would you likely
Relative influence of direct vs. indirect mechanisms?	Which factor has a bigger impact on your innovation activities? The market growth for renewables or the support policy for renewables?
Additional factors that affect innovation activities	What other factors determine innovation activities in your business?
	Which role does innovation in other sectors play, e.g. the automobile industry, for your business?
	Which role do support policies for your technology play for your innovation activities?
	What role do regulatory actions play for your innovation activities?
	Which role does the availability of additional internal/external funds for R&D play for your innovation

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Volker H. Hoffmann is Professor for Sustainability and Technology and the former Head of the Department of Management, Technology and Economics of ETH Zurich (2011–2014). He received a diploma in chemical engineering from ETH Zurich in 1997 and a diploma in business administration from the University of Hagen, Germany, in 1999. In 1996/97 and 1999/2000 he worked as a visiting scholar and scientist at MIT where he investigated uncertainty propagation in large-scale process models for the chemical industry (group of Gregory J. McRae). In 2001, he obtained his Ph.D. from ETH Zurich with a thesis on multi-objective decision making under uncertainty in chemical process design (group of Konrad Hungerbühler). Before joining the faculty of ETH Zurich in 2004, he was a project manager at McKinsey & Company where he worked in the chemical and electricity industry.

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