The Impact of Innovation Policy on Firm Behavior: An Empirical Analysis of the Energy Sector

Dissertation zur Erlangung des Grades eines
Doktors der Wirtschaftswissenschaft

eingereicht an der Fakultät für Wirtschaftswissenschaften
der Universität Regensburg

vorgelegt von: Josef Plank, Master of Science with Honors

Berichterstatter: Prof. Dr. Michael Dowling (Erstgutachter)
Prof. Dr. Roland Helm (Zweitgutachter)

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UNIVERSITÄT REGENSBURG

Fakultät für Wirtschaftswissenschaften

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Regensburg, den 4. Mai 2018

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List of Acronyms

ACAP	Absorptive capacity
Avg.	Average
BM	Business model
e.g.	For example (exempli gratia)
et al.	And others (et alii)
ETIS	Energy technology innovation system
i.e.	That is (id est)
IEA	International Energy Agency
IPC	International Patent Classification
IS	Innovation system
NIS	National innovation system
No.	Number
OECD	Organisation for Economic Co-operation and Development
p.	Page
PACAP	Potential absorptive capacity
Ppt	Percentage points
PV	Photovoltaic
RACAP	Realized absorptive capacity
R & D	Research & Development
RBV	Resource based view
RIS	Regional innovation system
RE	Renewable Energy
SIS	Sectoral innovation system
TIS	Technological innovation system
VHB	Verband der Hochschullehrer für Betriebswirtschaft e.V.
VIF	Variation inflation factor

1. Introduction

As “[…] firms seldom innovate in isolation” (Fagerberg et al. 2006, p.180), scholars do not analyze innovation primarily on a segregated firm-level but apply a more systemic perspective instead. This broader systemic perspective, i.e., the “innovation system” (IS), has been commonly applied in the scientific and political world for decades (Edquist 1997). Although the literature on the IS perspective remains fragmented and taxonomies between authors differ, some key characteristics have been identified. First, innovation is not the outcome of a linear R&D process within a singular firm. It is the result of interactive learning processes between various actors, which are connected through networks and guided by institutions within a given IS (Freeman 1995; Johnson 1997; Edquist 1997). Second, the term "actors" covers firms, their customers, suppliers, and competitors as well as research institutes, banks, universities, and governmental bodies. They are all linked directly or indirectly, thus contributing to the creation and diffusion of innovation deliberately or by chance. Third, institutions influence a firm’s behavior and enable or hamper its innovativeness through incentives, guidance, and restrictions (North 1990). They can be formal (e.g. laws, regulations, public policies) or informal (e.g. cultural norms, social rules, technical standards, common beliefs, perceptions) (North 1990; Edquist, Johnson 1997; Scott 2014). Fourth, knowledge and interactive learning processes are at the core of an IS perspective (Lundvall 1992; Edquist 1997). Given these four characteristics, I choose the IS perspective as the theoretical basis of my dissertation in order to discuss the impact of innovation policy on firm behavior. I examine how institutional influences and interactive learning between firms, universities, and governmental bodies affect a firm`s innovative performance and ability to capture external knowledge. Although it has been an established theoretical framework since the late 1980s (e.g., Freeman, 1987;

Carlsson, Stankiewicz 1991; Lundvall 1992; Nelson 1993), underexamined research areas and conceptual shortcomings for the IS perspective remain. I address two distinctive aspects of the IS perspective in this dissertation, i.e. the impact of innovation policy on firm-level innovativeness (Research Question 1) as well as knowledge and learning processes (Research Question 2).

For Research Question 1 and according to institutional theory (North 1990; Oliver 1991, 1997; Scott 2014), a firm’s behavior, strategic orientation, and decision-making is dependent on the institutional environment. A large number of studies within the context of the IS perspective highlight that this causal relationship also holds true for a firm`s innovation process, i.e., institutions enable, guide, or constrain a firm`s innovation performance (Edquist, Johnson 1997; McKelvey 1997). Nevertheless, the causal relations between actors and institutions are yet to be fully determined. Reasons for this research gap include the variety and complexity of institutional influences, the diversity of actors and their unpredictable individual behavior as well as a lack of sophisticated innovation input and output metrics for measuring the normative dimension of institutional influences on an actor's innovativeness (Stenzel, Frenzel 2008; Edquist, Johnson 1997; McKelvey 1997; Autant-Bernard et al. 2013). I address this gap with the first research question of my dissertation.

Research Question 1: How does innovation policy affect firm-level innovation within an innovation system?

The second aspect of the IS perspective that I discuss covers the most important resource of the modern economy: knowledge and its underlying process of learning (Lundvall 1992). Knowledge creation and diffusion are key determinants of an innovation system, but research dedicated to the interactive learning networks of the different actors remains sparse (Johnson 1997; Lundvall 2016). This is surprising as enhanced communication methods, increasing global trade volumes, the existence of multinational firms, and a higher degree of employee mobility facilitate the exchange of knowledge between firms, countries, and sectors. Key challenges include recognizing how different kinds of knowledge emerge and how to best measure them. These questions can only be solved by focusing directly on knowledge processes in the firm`s R&D departments (Lundvall 2016). Cohen and Levinthal (1989, 1990) were among the first scholars to define the determinants needed by a firm in order to create internal knowledge and capture external knowledge. This led them to develop the theory of absorptive capacity. I apply their theory on which factors determine a firm`s ability to capture external knowledge to the IS perspective. By doing so, I contribute to a better understanding of knowledge and interactive learning processes on a firm-level perspective.

Research Question 2: Which factors determine a firm's ability to acquire external knowledge within an innovation system?

Although both research questions are applicable for the different sub-streams of the IS perspective (see 1.1.2), I discuss them within the energy technology innovation system (ETIS). The ETISis described in more detail in Chapter 1.1.3 and can be defined as following:

"The ETIS is the application of a systemic perspective on innovation to energy technologies comprising all aspects of energy systems (supply and demand); all stages of the technology development cycle; and all innovation processes, feedbacks, actors, institutions, and networks." (Gallagher et al. 2012, p. 139)

I decide to focus on the ETIS for various reasons. First, energy technologies worldwide are highly influenced by institutions (e.g., through global climate agreements; public subsidy schemes for renewable energies; regulations on energy efficiency, security, and emissions), which makes ETIS an interesting research field for examining institutional influences on firm-level innovation (Jacobsson, Lauber 2006). Second, a more systemic understanding of knowledge and learning processes is necessary for the implementation of energy technologies in order to decrease development -, production-, and maintenance-costs for new (renewable) energy technologies and to adopt public funding policies accordingly (Sagar, van der Zwaan 2006). The ETIS allows to analyze the various dimensions of knowledge diffusion and learning relevant for energy technologies. The ETIS implies a subjective level for various jointly innovating actors (e.g., firms with suppliers, customers, competitors, and universities), a global level to account for international development and production value chains (Zhang, Gallagher 2016) as well as an intersectoral level for the dependency from and applicability to other sectors, e.g., the chemical, electronics, and electrical sectors (Nemet 2012). This complexity is indeed challenging, but it also provides an abundance of data for analysis. Third, research on a more systemic perspective is required to overcome slow energy technology diffusion rates (Negro et al. 2012) and to help energy firms to better leverage their relatively small R&D spending (energy & chemical firms account for 5.5% of global R&D spending, compared to, e.g., computing and electronics 24.0%, healthcare 22.1% and automotive 15.4% (Statista 2016). Furthermore, due to deregulation and privatization, increasing prices for fossil fuels, and an emergence of renewable energy technologies, the pressure to innovate is rising and thus a more systemic perspective on energy technologies is necessary (Sagar, Holdren 2002).

In summary, a better understanding of how innovation policy affects firm-level innovation as well as of knowledge and interactive learning processes has become increasingly important for the implementation of energy technologies. This has resulted in the systemic perspective of the ETIS. Innovation mainly occurs through a network of various actors, which own knowledge from applied and basic research as well as from different sectors and countries (Gallagher et al. 2012). The two above research questions i.e. the impact of innovation policy on firm-level innovativeness (Research Question 1) as well as knowledge and learning processes (Research Question 2) within an innovation system, are thus not only applicable to the ETIS, but also of high scientific, political and public interest. In **Paper 1**, I address the first research question by examining how public R&D funding as a financial resource influences renewable energy firms' innovative performance. I find empirical support for a positive effect of public R&D funding on the quantity of product and process innovations, but not on their quality measured by patent and citation data. In **Paper 2**, I also contribute to the first research question, but focused on business model innovation and institutional influences through laws and regulations. The results of the qualitative case-study of Paper 2 are by their nature not generalizable. However, they indicate under reserve that energy incumbent firms innovate their business models at a different scope, direction, degree, and frequency depending on the institutional influences of different energy markets. In **Paper 3,** I focus on the second research question on knowledge and learning. I highlight the importance of international and intersectoral knowledge flows for the German photovoltaic (PV) sector based on a patent-citation analysis of data since 1976 and defined determinants for a firm`s knowledge absorptive capacity.

The dissertation comprises five chapters. In the first part of Chapter 1, I introduce the IS perspective and discussed the need for and emergence of the ETIS. In the second part of Chapter 1 (Section 1.2), I summarize the distinctive theories, contents, and methodologies of the three papers, which then follow in Chapters 2, 3, and 4. In Chapter 5, I link the research needs of the ETIS with the key findings of the three papers and then review their research contributions and their managerial and political implications. I conclude my dissertation with limitations and future research opportunities.

1.1 Introduction to the Energy Technology Innovation System (ETIS)

1.1.1 Theoretical Background on Innovation Systems

In this section, I introduce the broader theoretical concept of the IS perspective in order to provide a clearer understanding of the ETIS. The origins of the IS perspective are found in work by Freeman (1987), Nelson (1984, 1988, 1993), and Lundvall (1988, 1992), who analyzed divergences in nations' innovation outcomes in the form of empirical case studies. The first reason for the emergence of the IS perspective was an observation that the Schumpeterian view of an individual inventor as the origin of innovation is in need of revision since firms today are innovating in interactive rather than linear and isolated processes (Kline, Rosenberg 1986; Edquist 2006). For the innovating actors, these interactive processes imply a certain degree of dependency on each other, the need to react to institutional influences, a high level of internal and external communication with user feedback, and thus an embeddedness within a larger innovation system. A second reason for the development of the IS perspective is the diversity of actors, their different access to technology, and their capability to use it, which is neglected in standard economics and business research (Lundvall 2016). Third, knowledge and the underlying process of learning have become central elements of modern economies (Lundvall 1992), but have not been adequately reflected in economic and business theory (Lundvall 2016). To overcome these shortcomings and better understand innovation processes, the more systemic perspective of innovation systems has emerged as a combination of interactive learning theory and evolutionary theories on technical change (Edquist 1997). This further theoretical development of the IS perspective leads to a variety of definitions, which are presented in Table 1.

Author	**Year**	**Definition**
Freeman	1987	"[…] The network of institutions in the public and private sectors whose activities and interactions initiate, import, modify, and diffuse new technologies" (Freeman 1987, p. 1)
Lundvall	1992	"[…] a system of innovation is constituted by elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge […]" (Lundvall 1992, p.2)
Edquist	2006	"The determinants of innovation processes = all important economic, social, political, organizational institutional and other factors that influence the development, diffusion, and use of innovations." (Edquist 2006, p. 182)
Hekkert et. al.	2007	"The concept of 'innovation systems' is a heuristic attempt, developed to analyse all societal subsystems, actors, and institutions contributing in one way or the other, directly or indirectly, intentionally or not, to the emergence or production of innovation." (Hekkert et al. 2007, p. 414)
Lundvall	2009	"The (national/regional/sectoral) innovation system is a focusing device aiming at analysing and understanding processes of innovation (rather than allocation) where agents interact and learn (rather than engage in rational choice). The aim of using this device is to find out which alternative institutional set-ups support strong dynamic performance of a (national/regional) economy or sector." (Lundvall 2009, p. 6/7)

Table 1: Selected Definitions of the Term "Innovation System"

Two features are common throughout these definitions: the *elements* of an IS perspective and its *purpose*. The elements include *actors (respectively organizations[1])*, *institutions,* and their

[1] Both terms exist in IS literature interchangeably (Doblinger 2013).

relations, which form an innovation system as a coherent whole (Edquist 2006). *Actors* within the IS perspective are formal structures that have been created consciously with a specific aim (Edquist, Johnson 1997). They include firms and their customers, suppliers as well as competitors, research institutes, universities, financial entities, governmental bodies or non-governmental organizations such as environmental groups and trade associations. *Institutions*, in contrast, regulate the relations and interactions of individual actors and groups. According to (North 1990), *institutions* can be formal or informal. Formal institutions include rules, laws, regulations, and public policies, whereas informal institutions consist of norms, traditions, common beliefs as well as established standards and practices. Scott (2014) adds that *institutions* provide stability and orientation for social interactions and distinguishes between regulative, normative, and cognitive *institutions*. His view on regulative institutions corresponds to the formal institutions of North (1990) and his definition of normative plus cognitive institutions constitutes the informal institutions of North (1990). An *institution*’s existence and effectiveness in guiding actors depends on its legitimacy (Carlsson, Stankiewicz 1991). In the context of the IS perspective, institutions determine a firm`s behavior as they reduce uncertainty, manage conflicts and cooperation, and provide incentives (Edquist, Johnson 1997). Important examples of institutions in the IS perspective are patent laws, public innovation policy (e.g., R&D funding schemes, regulations for industry-university R&D collaboration, educational systems) as well as environment and safety regulations (Edquist 2006). Finally, (North 1990) describes the *relation* between both *actors* and *institutions* in a condensed way that describes *actors* as players and *institutions* as the rules of the game. A key assumption of both institutional theory and the IS perspective is that *institutions* define the individual *actor*`s behavior in terms of scope, direction, degree, and frequency through incentives, guidance, and constraints. The second feature of an IS perspective is its *purpose*, which is to develop, diffuse, and use innovations (Edquist 2006). Both Edquist (2006) and Hekkert et al. (2007) summarize a list of functions of the IS perspective that should be in place in order to foster innovation. These functions include the promotion of entrepreneurial activities, network building, search guidance, market formation, and financing of innovation. As the focus of the dissertation lies, however, on the relations between actors and institutions as well as on knowledge and learning, I will not discuss the functions of an IS perspective in more detail but refer instead to the corresponding literature (e.g., Edquist 2006; Hekkert et al. 2007; Bergek et al. 2008; Bergek 2011).

In summary, the strengths of the IS perspective are its holistic view as well as its focus on the interdependencies between actors and institutions, which makes it an useful tool for analyzing innovation for scholars, managers, and politicians (Edquist 2006). Unlike standard economics and business theory, the IS perspective also accounts for the diversity of actors and emphasizes the importance of knowledge creation and learning processes (Lundvall 2016). Finally, it allows us to account for various types of innovation (Edquist 2006). Weaknesses are found in the absence of a profound theory for deducting propositions and allowing empirical testing (Giesecke 2000) as well as conceptual ambiguities in key terms (Edquist 2006). Furthermore, the IS perspective is a static rather than a dynamic concept and focuses on institutional influences instead of a firm-level perspective (Hekkert et al. 2007). In order to overcome these weaknesses and sharpen the scope and definitions, different sub-streams of the IS perspective for specific units of analysis have emerged, which will be introduced in the next section.

1.1.2 Distinction between the Sub-streams NIS, RIS, SIS, and TIS

The further theoretical development of the IS perspective evolves within different system boundaries and can be clustered into national innovation systems (NIS) (Freeman 1987; Freeman

1995; Lundvall 1992; Nelson 1993), regional innovation systems (RIS) (Cooke 1992, 2001; Saxenian 1996; Morgan 1997; Asheim et al. 2011), sectoral innovation systems (SIS) (Breschi, Malerba 1997; Malerba 2002), and technological innovation systems (TIS) (Carlsson, Stankiewicz 1991; Hekkert et al. 2007; Bergek et al. 2008).

Niosi et al. (1993, p. 212) provide a first conclusive definition of the NIS as "[…] system of interacting private and public firms (either large or small), universities, and government agencies aiming at the production of science and technology within national borders. Interaction among these units may be technical, commercial, legal, social, and financial, in as much as the goal of the interaction is the development, protection, financing or regulation of new science and technology." In a later work, Niosi (2002) lists a variety of definitions for the NIS, which all include the general assumption that national boundaries such as public policies, cultural norms, language, networks, and infrastructures define the innovation processes. As one of the first studies to do so within this field, Freeman (1987, 1988) explains the successful development of the Japanese IS based on specific national characteristics, i.e., the role of central governmental bodies, knowledge sharing between Japanese firms, firms` R&D organization, and the importance of the Japanese educational, training, and social system. An additional argument for innovation occurring inside national boundaries is the importance of tacit knowledge, which is restricted to people mobility (Niosi 2002). Within the NIS, the analysis of innovation occurs on an aggregated national level, which covers the R&D activities and linkages of firms, universities, and governmental bodies under a given institutional setting (Carlsson et al. 2002). In contrast to this aggregated view, the RIS elaborates innovation on a more granular geographic level It evolved mainly from empirical studies on the Silicon Valley and Route 128 (Saxenian 1996) and various European regions (Cooke 1985;

Cooke, Morgan 1994; Morgan 1997). Though it follows the same logic as the NIS, it argues for a more regional unit of analysis to better capture local policies, networks, market structures, collective learning initiatives, local labor markets, or differences in the population and infrastructure of regions (Cooke 1992; Asheim et al. 2011). Unlike the RIS, the SIS argues that innovation can be understood better on a sectoral rather than a geographic level as innovation is subject to different technological regimes, knowledge stocks, and technological development opportunities driven by cooperation and competition (Carlsson et al. 2002; Binz, Truffer 2017; Breschi, Malerba 1997). A key characteristic of the SIS is the focus on private firms and the examination of both vertically and horizontally linked actors, which contradicts a certain geographic limitation (Breschi, Malerba 1997). Critics of the SIS point to the neglect of non-firm actors and informal institutions as well as missing causalities for the emergence of new sectors (Binz, Truffer 2017).

Criticism has been levelled against the narrow perspectives of the NIS, RIS and SIS as they neglect supranational legislations and organizations, increasing global trade volumes and division of work, the internet and enhanced communication infrastructures, blurring industry boundaries, and the existence of multinational firms operating in diverse sectors and countries (Hekkert et al. 2007; Binz, Truffer 2017). In summary, these factors lead to a higher level of international and intersectoral knowledge flows and technology diffusion. Thus, the allocation of innovation to a distinctive nation, region, or sector is no longer appropriate, which shifts the focus towards the underlying technology and the emergence of the TIS. Carlsson and Stankiewicz (1991, p.94) define the TIS as "[…] network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion and utilization of technology."

The TIS focuses on the technological characteristic of an innovation and allows us to explain the dynamics of knowledge and competence networks (Carlsson, Stankiewicz 1991) as well as the emergence of new technologies and their relation to incumbent technologies over time (Hekkert et al. 2007). This in turn facilities the development of corresponding innovation policies (Archibugi, Lundvall 2002).

In conclusion, the above reviewed innovation systems discuss interactive innovation processes of linked actors and institutions from different perspectives. They should therefore be open and flexible depending on the researcher`s interest (Lundvall 1992) and supplement rather than substitute each other (Edquist 1997; Johnson 1997). Consequently, a common understanding of the IS literature is that its sub-systems NIS, RIS, SIS and TIS overlap and interact (see Figure 1) (Bergek et al. 2008; Hekkert et al. 2007; Binz, Truffer 2017; Asheim et al. 2011).

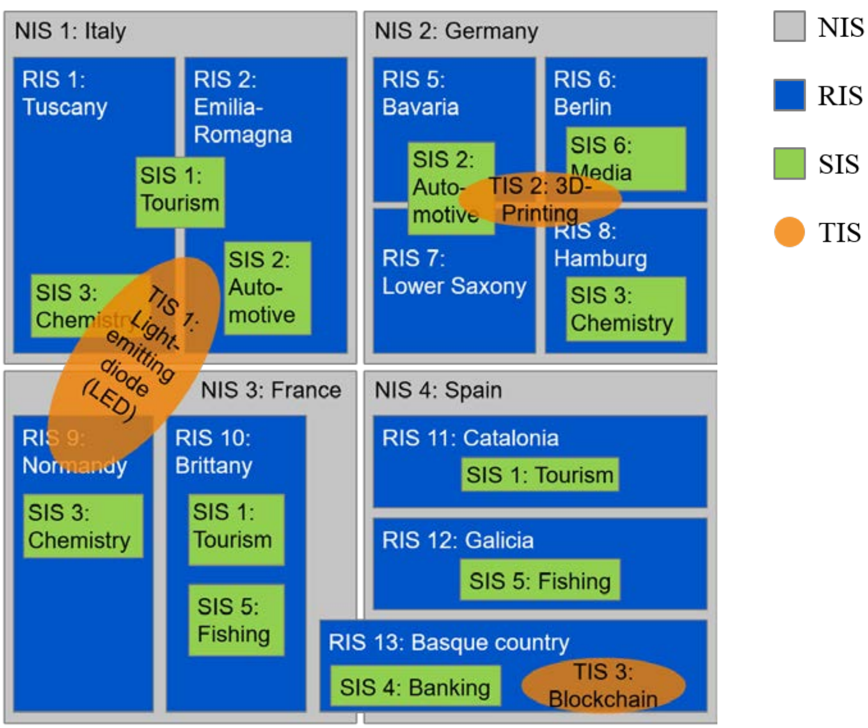

Figure 1: Illustrative Example to Conceptualize the Relations between NIS, RIS, SIS and TIS adapted from Hekkert et al. (2007)

As the objective of this dissertation is to examine how innovation policy affects firm behavior in the context of energy technologies, I will now outline why a distinctive ETIS emerged from the IS perspective literature and describe its key characteristics.

1.1.3 Relevance and Definition of the ETIS

The reasons behind the development of ETIS with elements of NIS, SIS, and TIS are manifold. First, the previously discussed analysis perspectives of the NIS, SIS and TIS are not applicable for energy technologies. The NIS has shortcomings as energy innovation occurs on a global level through multinational firms and both national and supra-national organizations determine the diffusion of energy technologies (e.g., United Nations, International Atomic Energy Agency Organization of the Petroleum Exporting Countries, International Energy Agency, World Bank, European Union). The SIS does not fully appreciate the strong dependencies between the energy sector and the chemical, electronics or electrical sectors (Nemet, 2012) as well as the high applicability of energy technologies for other sectors, e.g., automobile, computer, building, infrastructure. The TIS implies a limitation if it`s only applied to one specific technology. In the context of energy technologies, however, there will inevitably be dependencies between the different energy technologies in terms of co-creation, diffusion, knowledge spillovers, regulations, and clustering (Gallagher et al. 2012). The various technologies include energy supply, storage, and demand technologies; traditional fossil-fuel energy and renewable technologies; centralized large-scale industrial and decentralized small-scale private technologies as well as mature, cost-efficient, and upcoming, expensive niche-technologies. Second, energy technologies need to consider distinctive characteristics. These include high capital intensity, long-range learning and development cycles, longevity of capital stock, intense competition as well as dependencies between established and new technologies, uncertainty of R&D outcomes, and strong “lock-in” effects (Grübler et al. 2012; Gallagher et al. 2012). Third, the public and political willingness to transform the energy sector from fossil fuels to renewable energy as well as its importance for global welfare results in an increasing scientific interest in how innovation policy has an impact on firm innovation behavior and how knowledge diffuses within the energy sector (e.g., Jacobsson, Bergek 2004; Jacobsson, Lauber 2006; Negro et al. 2007) .

Jacobsson, Johnson (2000) and Sagar, Holdren (2002) are some of the first scholars to call for a systemic perspective on energy technology innovations. Finally, Gallagher et al. (2006) address the need to structure existing studies on energy technologies more systematically and lay the foundation for the ETIS.

Gallagher et al. (2012, p. 139) **define the ETIS** as “[…] application of a systemic perspective on innovation to energy technologies comprising all aspects of energy systems (supply and demand); all stages of the technology development cycle; and all innovation processes, feedbacks, actors, institutions, and networks.”

Based on this initial definition, five important elements emerge. First, the scope of actors includes energy firms and their network of suppliers and customers, governmental bodies, financial institutions, research institutes and universities, energy-related NGOs (e.g., Ceres, Natural Resources Defense Council, Greenpeace) as well as local public movements. Of these, energy firms are heterogeneous and range from incumbent utility suppliers, manufacturers of certain energy technologies such as PV modules or wind turbines to start-ups with new business models in the field of, e.g., virtual power plants, weather forecast, or project development via crowd-founding.

Among the actors in an ETIS, customers are highly interesting as they take the more active role of "prosumers" in the future energy technology system. Second, formal institutions in the context of ETIS include all laws and regulations relevant for the provision, distribution, and use of energy. They range from the global Paris climate agreement, bilateral contracts on energy trading, national laws on energy security, efficiency and subvention (e.g., the nuclear phase out in Germany by 2022, Renewable Energy Source Act (EEG)) to local regulations about, e.g., the construction of wind turbines and photovoltaic parks. Informal institutions in the context of ETIS include norms, habits, common practices, and traditions, e.g., about domestic energy usage and environmental awareness. Third, collective learning and knowledge spillovers between various actors highlight the importance of networks within the ETIS (Grübler et al. 2012). Networks can be formal and long-term orientated (e.g., supplier-relationships, co-patenting activities, industry-university R&D collaboration, open lab programs), but also informal (e.g., personal contacts, conferences, trade fairs) (Azagra-Caro et al. 2017). Fourth, the phase of market formation during the interactive innovation process is an important function for the ETIS in order to stimulate demand for not yet mature and costly new technologies such as PV, wind, biofuels, and biomass (Hekkert et al. 2007; Grübler et al. 2012). Fifth, energy technologies cover the three clusters energy supply, storage, and demand technologies. *Supply* side technologies enable the energy production and include nuclear, fossil fuel, and renewable energy technologies. Energy *storage* technologies are primarily electrochemical battery technologies, but also exist in various other forms, such as mechanical (e.g., pumped-storage hydroelectric), chemical (e.g., power-to-gas, biofuels, hydrogen), or thermal. *Demand* side technologies include all energy-consuming technologies as well as the variety of smart grid and metering applications for balancing the energy system. All three clusters of energy technologies are affected by digitalization, which combines energy and information flows along the entire chain from energy production to consumption in both directions. Digitalization enables new process, product, and business model innovation, which makes it a central element within the ETIS. Evolving examples include the establishment of decentralized virtual power plants, optimized energy supply forecast of renewable energy through the inclusion of real-time weather data, predictive maintenance of wind rotor blades via fiber-optic sensors, improved customer satisfaction through mobile billing and metering as well as smart home and connected building applications.

Having provided a comprehensive introduction to the ETIS, I will now describe future research needs and demonstrate the importance of the above two research questions.

1.1.4 Identified Research Needs of the ETIS

Research on ETIS should examine the dimensions (a) the role of actors and institutions, (b) knowledge and learning, and (c) enhanced research methodologies and data (Gallagher et al. 2012; Grübler et al. 2012). The first research area on (a) the role of actors and institutions is at the core of each IS perspective. It examines how institutions affect individual actors and whether these influences constrain or enable innovation, which directly corresponds to my first research questions about the impact of innovation policy on firm-level innovativeness. The challenge for researchers lies in the multi-dimensional and fragmented causal relations that are difficult to measure. For example, the institutional influence on firm-level innovation can only be clustered broadly into technology-push and demand-pull policies, but consists in practice of a variety of simultaneously implemented political instruments that have to be aligned with the interests of incumbents and new entrants, other actors such as private and industrial end-users as well as research institutes. In addition, these institutional influences have to be both stable, to allow long-term investments into new technologies and further technology development, and flexible and broad, to stimulate competition between various energy technologies and actors (Gallagher et al. 2012). A better understanding of the interdependencies between actors and institutions would thus enable a more efficient and effective promotion of new energy technologies and increase social well-being.

Closing the research gaps on (b) knowledge and learning is addressed by my second research question and is highly important within the ETIS for two reasons. First, energy technologies are typically the combination of various technological components from different sectors (e.g., engineering, chemical, electronic, communications), the synthesis of applied (private firms) and basic research (universities, research institutes) as well as the result of global value chains and intense user feedback. Thus, the exchange of knowledge and the improvement of learning capabilities are fundamental for energy firms in order to create and further develop energy technologies. Second, knowledge creation and learning processes are key enablers for the diffusion of emerging energy technologies such as renewable energies as they enable firms to reduce their development and production costs significantly in order to compete with mature fossil fuel technologies. To enable knowledge and learning processes, energy firms and scholars in the field of ETIS first have to gain a better understanding of international and intersectoral knowledge spillovers. Secondly, the ETIS lacks a theoretical deduction of determinants for a firm`s knowledge absorption capacity as well as empirical insights on success factors for effective R&D structures and collaboration (Gallagher et al. 2012).

For (c) methodologies and data, conceptual models have to define reliable and internationally applicable innovation input and output metrics. They should abandon their primarily descriptive nature and focus on the causal relations between the variables of the ETIS through hypotheses testing (Gallagher et al. 2012). Concrete data needs include private firm-level R&D activities, public and private technology investments, information about global and intersectoral knowledge spillovers as well as the extension of data to non-OECD countries (Gallagher et al. 2012). Finally, the research frameworks have to be dynamic rather than static in order to reflect developing energy technologies as well as changing market structures, firm behavior, and public policies.

To meet the research requirements of (a), (b) and (c), I formulate the two overarching research questions accordingly, i.e. I discuss the impact of innovation policy on firm-level innovativeness (Research Question 1) and examine knowledge and learning processes (Research Question 2) within the ETIS. In addition, I specify the two overarching research questions to a total of five paper-specific research questions and design three dedicated research methods. I run an intense data collection effort for historical, granular, but also comprehensive innovation input and output data as well as information on the different institutional influences. Finally, I choose a cumulative structure for my dissertation as it enables me to combine distinctive theories and methodologies in combination with the ETIS to guarantee a profound theoretical foundation and sophisticated conceptual models, as outlined in the next section.

1.2 Overview of the Dissertation

1.2.1 Theoretical Framework

Figure 2 shows the theoretical framework of the ETIS, which consists of the three levels government, firms, and other actors. It also illustrates how each of the three papers is embedded within this framework and links different levels of the ETIS. The color-coded arrows illustrate how I address diverse dimensions within the ETIS in each paper, i.e. public R&D funding, laws and regulations as well as knowledge. In **Paper 1**, I analyze how governments influence firm-level innovativeness through financial incentives in the form of supply-push policies. In **Paper 2**, I broaden the scope of governmental influences to supply-push and demand-pull policies, i.e., the sum of laws and regulations that affect the innovativeness of energy utilities. Finally, in **Paper 3**, I focus on knowledge and interactive learning processes between various firms and through industry-university R&D collaborations.

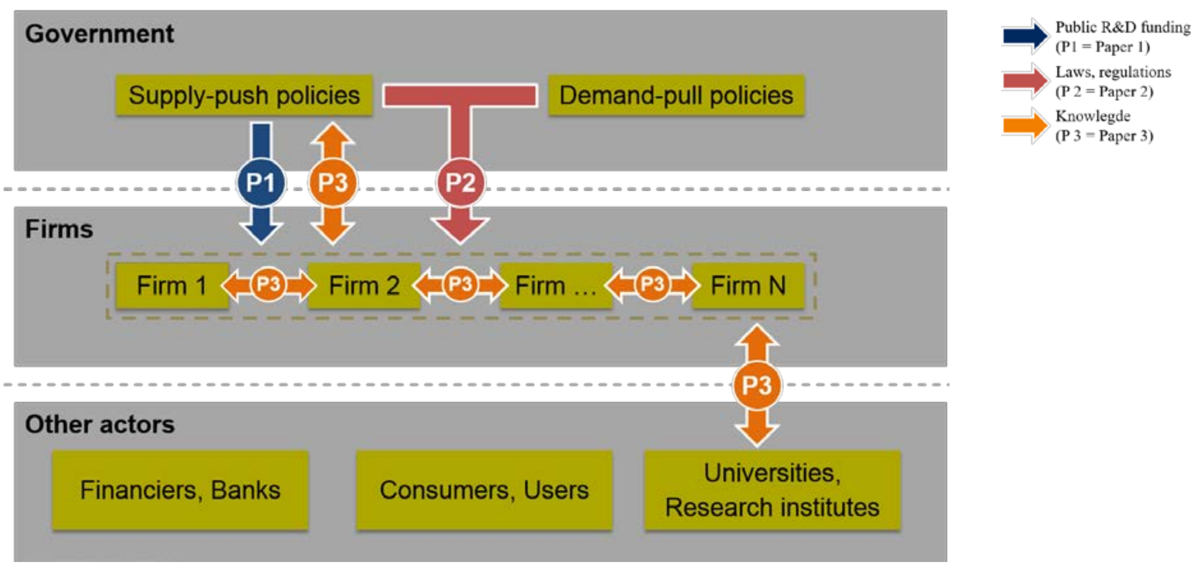

Figure 2: Theoretical Framework of the Dissertation adapted from Gallagher et al. (2006)

1.2.2 Structure and Content of the Three Papers

Table 2 shows the content of the three papers along its core dimensions to highlight the variety of research questions, discussed theories, applied methodologies, and self-created databases. **Paper 1** (co-authored with Dr. Claudia Doblinger) has been published in the journal Energy Policy, **Paper 2** has gone under review at Energy Policy and **Paper 3** at Research Policy.

	Paper 1	**Paper 2**	**Paper 3**
Title	The Firm-Level Innovation Impact of Public R&D Funding: Evidence from the German Renewable Energy Sector	Firm Strategic Behavior in Response to Europe`s Renewable Energy Policy – A Cross-Country Analysis	Drivers of Global Knowledge Spillovers in the Energy Sector and the Determinants of a Firm`s Potential Absorptive Capacity
Authors	Josef Plank Dr. Claudia Doblinger	Josef Plank	Josef Plank
Overarching research question	How does innovation policy affect firm-level innovation within an innovation system?	How does innovation policy affect firm-level innovation within an innovation system?	Which factors determine a firm's ability to acquire external knowledge within an innovation system?
Paper-specific research question(s)	(1) What role does public R&D funding as a financial resource have on firm-level R&D performance? (2) What other critical firm resources are key success factors for firm innovativeness?	How have European incumbent energy utilities adjusted their business models in response to legal environmental dynamics?	(1) What are the main characteristics of knowledge flows and patenting patterns affecting the German PV sector? (2) What factors determine a PV firm`s PACAP?
Theory	Resource-Based View (Wernerfelt 1984; Barney 1986, 1991; Dierickx, Cool 1989)	Contingency Framework on Business Model Dynamics (Saebi 2015)	Absorptive Capacity Theory (Cohen, Levin-thal 1989, 1990; Zahra, George 2002; Lane et al. 2006)
Methodology	Quantitative: Regression models	Qualitative: Multiple case-study	Quantitative: Regression models
Data	206 publicly granted R&D projects, 3,900 patent applications, and 8,500 citations	- Public corporate data - Laws of French, British, and German electricity markets	1,446 patent applications and 7,867 cited patents
Innovation	Product & Process	Business model	Product & Process
Research context	1,448 German wind & PV firms, 2006–2015	European energy incumbents, 2009–2017	129 German PV firms, 2006–2015
Status	Published in Energy Policy 113 (2018) 430–438 (VHB[2]: B)	Under review at Energy Policy (VHB[2]: B)	Under review at Research Policy (VHB[2]: A)

Table 2: Summary of the Three Papers of the Dissertation

[2] „Verband der Hochschullehrer für Betriebswirtschaft e.V.“ (VHB) evaluates scientific journals relevant to business research. Mentioned classification of the journals Energy Policy and Research Policy refers to VHB-Jourqual 3 from 2015, which lists 3.4% of journals as A+, 11.1% A, 33.3% B, 41.9% C and 9.1% D. Source: http://vhbonline.org/en/service/jourqual/vhb-jourqual-3, accessed on 12th September, 2017.

In **Paper 1** (co-authored with Dr. Claudia Doblinger, published in Energy Policy), we address Research Question 1 by discussing a specific instrument of innovation policy, i.e., public R&D funding and its impact on a firm`s innovative performance. Following the resource-based view (RBV), we argue that public R&D funding as a financial resource should positively affect a firm`s innovative outcome in a quantitative and qualitative manner. To empirically test our hypotheses, we analyze the innovative outcome in terms of patent application and citation data for 1,448 German renewable energy firms, out of which 489 firms received a total of 235 Mio € public R&D funding between 2006 and 2015. Our findings indicate a positive effect of the financial resource public R&D funding on patent quantity, but no significant effect on patent quality. In addition, we observe a positive relationship effect of past public R&D funding intensity, a firm`s overall financial situation, and its technology knowledge base on patent count; only a firm`s technology knowledge base has a significant positive effect on patent quality, while the other variables of interest have no significant effect. A firm`s physical resources have no significant effect on either patent quality or quantity. We thereby contribute to the RBV by linking a set of tangible and intangible resources with a firm´s innovative performance. We also gain empirical insights on the ETIS, we show how innovation policy affects a renewable energy firm`s innovative outcome using a distinctive dataset of public R&D funding and patent data. These insights enable policy makers to adjust current R&D funding criteria accordingly and thus invest public money more efficiently.

In Paper 2, I also discuss Research Question 1 about the impact of innovation policy on firm-level innovativeness. I examine how incumbent energy utilities adjust their business models in response to changing legal environments. Based on a multiple case-study of the energy utility EDF in France, SSE in the UK and E.ON in Germany between 2009 and 2017, I apply the theoretical contingency framework on business model dynamics put forward by Saebi (2015). As a first insight, I find support for her theoretical expectations that the frequency, amplitude, predictability, and velocity of environmental dynamics define the scope, radicalness, frequency, degree of novelty, and planned outcome of business model changes. The French incumbent EDF, in a constant legal environment, develops its business model naturally and gradually, with only an incremental radicalness. The British SSE, facing a more dynamic environment, constantly adjusts its business model along all dimensions. The German E.ON, confronted with a fundamental shift of its legal environment, implements the most radical and wide business model changes including the organizational split of Uniper. A second potential insight is the observation of common business model trends, which are independent of legal environments and mainly driven by increasing customer demands, technological developments (e.g., smart grid, small-scale storage and power generation solutions, smart home application), and higher competition. Based on the case-study sample, these trends include a broader value proposition towards servitization, a higher customer-orientation with personalized and digital energy applications, a growing share of renewable energy plants as key resources, and a financial shift towards regulated business. The theoretical findings not only enrich the contingency framework on business model dynamics put forward by Saebi (2015), but also contribute to the ETIS by creating a better understanding of the interaction of institutions and actors in four dimensions. First, the focus on incumbent firms complements the dominating studies on isolated renewable energy or decentralized business models (e.g., Engelken et al. 2016; Gabriel, Kirkwood 2016; Green, Newman 2017; Wainstein, Bumpus 2016; Strupeit, Palm 2016). Second, the applied dynamic view for the years 2009–2017 differs from established static frameworks (Richter 2012; Valocchi et al. 2014) and contributes to the research on firm-level implications of the Fukushima-accident in 2011 (Kungl 2015). Third, the cross-country analysis for the French, British, and German electricity markets accounts for the importance of different national contexts (Engelken et al. 2016; Kern, Markard 2016). Fourth, the detailed analysis of European and national energy laws and regulations adds a further perspective to the scientific discussion, which is dominated by technological developments. I suggest as practical implications for policy makers, transparent and timely communication on new legislation and an intense dialogue with the industry. Beneficial options for managers are the structured analysis of business model trends, an increased awareness of change, and a variety of strategic responses to environmental dynamics.

In contrast to **Papers 1** and **2**, I examine Research Question 2 on knowledge and learning processes within the ETIS in **Paper 3**. The applied methodology consists of two steps. Based on patent and citation data from the German PV sector between 1976 and 2015, I first, I detect patterns in R&D organizational structures and visualize international and intersectoral knowledge flows. Second, I empirically test hypotheses from the absorptive capacity (ACAP) theory (Cohen, Levinthal 1989, 1990; Zahra, George 2002; Lane et al. 2006) on inventor-related, inter-organizational, and other systemic determinants to identify how to best capture external knowledge on a firm level. The results indicate a fundamental increase in patent activity since the mid-1990s, with a growing importance of industry-university R&D collaboration, a higher participation rate by female inventors, and substantial dependence on international and intersectoral knowledge. (For the years 1976 to 2015: 58.19% of cited patents granted by German PV firms came from foreign firms and 48.51% of the cited patents originated from outside the PV sector.) Diversity among inventors, international and industry-university R&D collaboration as well as spatial proximity to universities increase a firm`s potential absorptive capacity (PACAP), i.e., the ability to acquire and assimilate external knowledge. In contrast, inter-industrial R&D collaboration and spatial proximity to other PV firms decrease a firm`s PACAP. This paper differs from previous studies as it discusses absorptive capacity theory in a holistic manner and applies it to a granular and objective patent and citation database. This new perspective contributes to the ETIS research in various dimensions. First, I satisfy the demand for a dynamic and transparent perspective of international and intersectoral knowledge spillovers based on globally comparable and reliable patent data for the period 1976–2015. Second, the documentation of structural changes in patenting patterns over time allows for insights into the dynamics of knowledge and learning modes on the firm level as well as the interactions of various actors within the ETIS. Third, I add to the theoretical foundation of the ETIS as I empirically test hypotheses from the absorptive capacity theory with respect to German PV firms. The analysis thus closes the central research gap of the ETIS regarding knowledge and learning processes as it defines inventor-related, inter-organizational, and other systematic determinants of how to best capture external knowledge on a firm level. These findings provide guidance to innovation managers on how to best structure their R&D departments and thus enable an energy firm to increase its innovation rate.

1.2.3 Theoretical Foundation of the Three Papers

Although Lundvall (2016) argues that the IS perspective is simply more complex but not less theoretical than standard economics, I follow Edquist (1997, p.30), who asserts that the IS perspective is "[…] a conceptual framework for the study of innovation processes rather than a formal theory." Given its limited degree of abstraction, the intellectual proximity to empirical results, and a lack of testified propositions to explain the causal relations of its variables, the IS perspective does not meet the requirements of a formal theory (Edquist 1997). The ETIS shares the same characteristic as the IS perspective as it originates from empirical studies and thus still requires an in-depth theoretical foundation (Gallagher et al. 2012). Consequently, I use the ETIS as a theoretical framework to structure my dissertation and substantiate it with established economic theories to strengthen its theoretical fundament (Edquist 1997), which I outline subsequently in more detail.

For **Paper 1**, Dr. Claudia Doblinger and I select the resource-based view (RBV) as the theoretical foundation. According to the RBV, a firm can be understood as a bundle of resources (Penrose 1959). These resources are the origin of a firm`s competitive advantage (Wernerfelt 1984; Barney 1986, 1991; Dierickx, Cool 1989). Barney (1991) specifies that a resource contributes to a firm`s competitive advantage if it is rare, non-substitutable, imperfectly imitable, and valuable. Given that public R&D funding as a financial resource fulfils these criteria, the RBV is a suitable theoretical foundation for explaining heterogeneous firms' competitive advantage manifested in divergent innovation performances. Furthermore, the RBV suggests and encourages the analysis of a variety of resources simultaneously (Galbreath 2005). This enables us to broaden our research setting and examine further tangible resources such as physical assets as well as intangible resources such as a firm`s technological knowledge base. A final argument for applying the RBV is the firm-level perspective of our paper.

In **Paper 2,** I deviate from the previous paper by discussing the influence of innovation policy on business model innovation instead of product and process innovation. Consequently, I combine the ETIS with the young and fragmented research field of business model innovation (Ramin 2017). Table 3 gives an overview of established definitions for business models.

Author	Year	Definition
Amit/Zott	2001	“The business model depicts the content, structure, and governance of transactions designed so as to create value through the exploitation of business opportunities.” (Amit, Zott 2001, p. 511)
Magretta	2002	“They are, at heart, stories – stories that explain how enterprises work. A good business model answers Peter Drucker’s age-old questions: Who is the customer? And what does the customer value? [...] How do we make money in this business? What is the underlying economic logic that explains how we can deliver value to customers at an appropriate cost?” (Magretta 2002, p. 4)
Mitchell/ Bruckner Coles	2004	“A business model is the combination of ‘who’, ‘what’, ‘when’, ‘where’, ‘why’, ‘how’, and ‘how much’ an organization uses to provide its goods and services and develop resources to continue its offers.” (Mitchell, Bruckner Coles 2004, p. 17)
Osterwalder	2004	“A business model is a conceptual tool that contains a set of elements and their relationships and allows expressing a company's logic of earning money. It is a description of the value a company offers to one or several segments of customers and the architecture of the firm and its network of partners for creating, marketing and delivering this value and relationship capital, in order to generate profitable and sustainable revenue streams.” (Osterwalder 2004, p. 15)
Morris et al.	2005	“A business model is a concise representation of how an interrelated set of decision variables in the areas of venture strategy, architecture, and economics are addressed to create sustainable competitive advantage in defined markets.” (Morris et al. 2005, p. 727)
Al-Debei et al.	2008	“The business model is an abstract representation of an organization, be it conceptual, textual, and/or graphical, of all core interrelated architectural, co-operational, and financial arrangements designed and developed by an organization presently and in the future, as well as core products and/or services the organization offers, or will offer, based on these arrangements that are needed to achieve its strategic goals and objectives.”(Al-Debei et al. 2008, pp.8/9)
Osterwalder/ Pigneur	2011	“A business model describes the rationale of how an organization creates, delivers, and captures value.” (Osterwalder, Pigneur 2011, p.14)

Table 3: Selected Definitions of the Term “Business Model”

Given the heterogeneity of the definitions, I apply the business model CANVAS, a conceptual framework of practical relevance (Osterwalder 2004; Osterwalder, Pigneur 2011). It consists of the four pillars value proposition, customer interface, infrastructure management, and financial aspects. In order to examine the influence of external factors such as innovation policy on business models over time, I combine the business model CANVAS with the contingency framework on business model dynamics put forward by (Saebi 2015). Within this framework, Saebi (2015) argues that distinctive environmental dynamics (regular change, environmental competitiveness, environmental shift) driven by institutional changes result in different types of business model changes (evolution, adaptation, and innovation) in terms of scope, planned outcome, degree of radicalness, frequency, and degree of novelty. This systematic causality between institutions and business model changes makes it an ideal theoretical concept for the ETIS to discuss how different national innovation policies affect an actor's business model innovation over time.

Regarding Research Question 2 on knowledge and learning processes, the ETIS emphasizes the importance of international and intersectoral knowledge spillovers for energy technologies. It calls for a better understanding of how actors can access external knowledge more efficiently, which has only been reflected in a limited number of empirical studies (Gallagher et al. 2012). I base **Paper 3** on the absorptive capacity theory as it suggests how firms identify, acquire, and incorporate external knowledge in order to apply it to commercial ends (Cohen, Levinthal 1989, 1990). I build on the further theoretical development of (Zahra, George (2002), who divide a firm`s absorptive capacity into a potential and realized absorptive capacity. The former consists of the two dimensions acquisition and assimilation of external knowledge; the latter includes knowledge transformation and exploitation. There are various reasons for why I focus on the potential absorptive capacity and combine it with the ETIS to define the antecedents of an energy firm`s capacity to acquire external knowledge. First, due to a rich set of theoretical and empirical studies. I am able to derive hypotheses on inventor-related, inter-organizational, and other systematic determinants for a firm`s potential absorptive capacity and apply it to the energy sector (e.g., Lewandowska 2015; Camisón, Forés 2010; Burcharth, Ana Luiza Lara de Araújo et al. 2015; Fosfuri, Tribó 2008; Enkel et al. 2017; Jansen et al. 2005; Volberda et al. 2010). Second, I can apply patent and citation data to operationalize the absorptive capacity theory reliably. Through the citation of patents, inventors prove that they have identified and understood external knowledge. Third, the theory is applicable to energy firms as they operate in an environment characterized by substantial external knowledge flows and run a significant level of own R&D activities, both of which are preconditions for firms to absorb external knowledge (Cohen, Levinthal 1989, 1990).

1.2.4 Methodology and Data

I apply different research designs in the three papers as the nature of the underlying research questions differs. In **Papers 1** and **3**, I discuss questions of *whether* and to *what degree* certain factors influence a firm`s innovative performance and/or its ability to absorb external knowledge. Consequently, I applied quantitative research designs, i.e. negative binomial and GLS regression models **(Paper 1)** and negative binomial regression models **(Paper 3)**. In **Paper 2**, in contrast, I examine *how* the external environment influences an energy incumbent’s business model, which is why I chose a qualitative case-study design (Yin 2009).

The co-authored, quantitative **Paper 1** analyses a sample of 1,448 renewable energy firms (596 photovoltaic firms, 852 wind firms) collected from business directories, insolvency registers, and the press. The relevant corporate data for the years 2006 to 2015 were taken from DAFNE (Bureau van Dijk), HOPPENSTEDT, and corporate websites. To measure the firm´s innovative performance in a quantitative and qualitative manner, we used patent and citation data from the DERWENT INNOVATIONS INDEX. The data source for the institutional influence, i.e., the amount and frequency of public R&D funding per firm, is the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (period 1977 to 2013) and the German Federal Ministry for Economic Affairs and Energy (2014 and 2015). We used the statistics software STATA and applied two separate models. Model 1 analyses the effect of public R&D funding on a firm`s R&D performance in a quantitative manner by applying a panel negative binomial regression model to a firm`s number of patent applications per year. Model 2 examines the qualitative implications of public R&D funding using a GLS random effects panel regression model on the average number of citations per patent application.

In **Paper 2**, I use a qualitative research method and apply a multiple case-study approach (Yin 2009) to Saebi's contingency framework on business model dynamics (Saebi 2015). I analyze institutional influences on the business models of three European energy incumbents, namely EDF in France, SSE in the UK, and E.ON in Germany. I use the structural framework of the business model CANVAS (Osterwalder, Pigneur 2011) with pre-defined business model elements to guarantee a high degree of comparability and reliability. As I examine business model changes for all business model elements and between 2009 and 2017, the research setting is universal and dynamic (Bieger, Reinhold 2011). I choose the French, German, and UK electricity sectors for theoretical reasons as each corresponds to one of Saebi`s environmental dynamics. i.e., regular change, environmental competitiveness, and environmental shift (Saebi 2015). To describe the relevant environmental conditions, I triangulate data from national governments, national regulatory bodies Ministries for Energy and Economy, the International Energy Agency, and Eurostat for the sample countries France, the UK, and Germany. The data source for business model changes of the three energy incumbent firms are annual reports, corporate websites, analyst reports (Hoover’s, MarketLine, Factiva), and semantic search strategies in business and financial newspapers (FACTIVA).

In Paper 3, I use a quantitative research method, i.e. negative binomial regression models and build on the corporate information of the PV firms from **Paper 1** as well as its patent application and citation data. Similar to **Paper 1**, I use the statistics software STATA and a negative binomial regression model to determine the antecedents of a firm`s capacity to capture external knowledge. In order to incorporate a more granular level of detail, **Paper 3** differs from **Paper 1** in three aspects. First, it is not a numeric but a content-related patent analysis, i.e., I extract per patent application data the number of inventors, their education, gender and cultural background as well as whether the patent applicant firm innovates in isolation or via national, international, and industry-university R&D collaborations. Second, I coded each cited patent along two dimensions that track whether it originates from inside or outside the PV sector and whether a foreign firm is listed among the patent applicants. This data processing effort enables me to account for different types of knowledge flows (total, international, and intersectoral), which only few studies do (Schmidt 2005). Third, I also account for relations with other actors in the innovation systems and control for governmental ties as well as the spatial proximity to other PV firms and universities.

In Chapter 1, I introduced the ETIS as the theoretical framework and briefly outlined the content and structure of the three papers. The following Chapters 2, 3, and 4 include the papers, which differ slightly from the submitted versions, as they have to meet the specific journal requirements.

2. Paper 1: The Firm-level Innovation Impact of Public R&D Funding: Evidence from the German Renewable Energy Sector

2.1 Introduction

Although the origin of the resource-based view (RBV) is found in strategic management literature (Barney, 1986, 1991; Wernerfelt, 1984), its linkage to research on firm-level innovation is of high scientific interest and has two important practical implications. First, the RBV supports innovation managers in identifying critical firm resources in order to maximize R&D performance and thus gain competitive advantage. Second, the RBV gives recommendations on how to finance critical firm resources. Besides internal financial resources, an innovation manager can leverage a variety of external financial resources, e.g., bank loans, stock market financing, venture capital, and crowd funding.

While the relevance of financial resources for firm-level R&D performance has been discussed in the context of the RBV (e.g., Del Canto and González, 1999; Galbreath, 2005; Lee et al., 2001), the role of public R&D funding has been neglected. This neglect is surprising as 28% of the gross domestic expenditure on R&D in 2014 within OECD-countries is spent by governments[3]. Furthermore, Nelson (1959) and Arrow (1962) highlighted the need for public R&D support decades ago: private firms do not invest in R&D projects at a socially desirable level as they cannot fully leverage the economic potential internally due to knowledge spillovers. Principal-agency theory gives evidence that the type of financing has an impact on R&D performance. While

[3] Source: OECD Research and Development Statistics (www.oecd.org/sti/rds)

asymmetric information, uncertainty about the R&D outcome, and limited control over the innovation process hinder R&D activity; flexible financial structures, culture of feedback and failure, focus on long-term success, and responsibility at the firm level all foster innovation (Bergemann and Hege, 2005; Holmstrom, 1989; Manso, 2011). The lack of granular grant data on the firm-level is a major reason why the effect of public R&D funding on firm-level R&D activity has not yet been fully explored (Belitz and Lejpras, 2016; Bérubé and Mohnen, 2009; Clausen, 2009).

On the other hand, there is a rich set of macro-economic studies on the effectiveness of public R&D funding for the energy sector (e.g. Johnstone et al. 2010; Peters et al. 2012; Bointner 2014). This research uses public R&D funding as an aggregated input factor to explain accumulated R&D outcome (e.g., patent stock, installed capacity, learning curves) on a macro level, with countries or sectors as the unit of analysis. The RBV, however, emphasizes the firm`s heterogeneity within the innovation process (Barney, 1991), which requires a more granular firm-level approach of analysis. Oliver (1997) links RBV and institutional theory, thereby underlining the importance of firm analysis since the strategic reactions of individual firms towards institutional influence differ.

These research gaps lead to two questions. (1) What role does public R&D funding as a financial resource have on firm-level R&D performance? (2) What other critical firm resources are key success factors for firm innovativeness?

To answer these questions, we derive hypotheses from the RBV and add empirical insights from prior studies on the effectiveness of public R&D funding. In particular, we use negative binomial and GLS panel regression models to measure the effect of financial, physical, and intangible resources on firm-level R&D performance for 1,448 German renewable energy firms. Our dataset consists of 206 publicly granted projects for the German photovoltaic (PV) and wind sectors, with a volume of approx. 235 Mio € between 2006 and 2015. We analyze approx. 3,900 patents and 8,500 patent citation data to evaluate individual firm-level R&D performance. First, our findings show that public R&D funding, a higher past funding intensity, and a firm`s overall financial situation have a significant positive effect on the quantity of firm-level innovation activity in terms of patent count but not on their technological or economic value measured by patent citation data. Second, a firm’s technological knowledge base as an intangible resource has a significant positive effect on both patent quantity and quality, while total assets as an indicator for physical resources have no significant effect.

Our findings contribute to linking RBV and innovation research by exploring whether public R&D funding can serve as a financial resource to promote innovation. Four different contributions are of great interest. First, previous studies on financing innovation focus primarily on equity, bank loans, or venture capital, and neglect public R&D funding (Hall and Lerner, 2010), especially in empirical studies (Howell, 2016). As the cost and incentive structure of public R&D funding is different, we provide practical implications on effective R&D financing. Second, we not only explore public R&D funding as a critical firm resource for innovation, but also a firm`s overall financial situation, its accumulated technology knowledge base, and the amount of physical resources. This is highly relevant as Galbreath (2005) attaches importance to using a comprehensive set of resources rather than isolated ones. Third, our research effort enables us to use granular data on firm resources, firm-level R&D performance, and public R&D funding data compared to the primarily more aggregated approach of previous research where the main focus was on evaluating different policy instruments (e.g., Johnstone et al., 2010; Olmos et al., 2012; Polzin et al., 2015) and crowding-out effects (e.g., Clausen, 2009; Dimos and Pugh, 2016; González and Pazó 2008). Fourth, the institutional nature of public R&D funding and its empirical application to the German renewable energy sector contributes to the literature on energy technology innovation systems (Gallagher et al. 2006; Gallagher et al. 2012; Grübler et al. 2012). It advances new knowledge within one of its core research gaps: the interaction of actors and institutions in the innovation process.

This paper offers corporate innovation managers insights into the trade-off between the benefit of public financial resources for firm`s R&D activities and the required efforts for the grant application and documentation as well as the disclosure of project results. In addition, it defines key success factors for developing innovations in the field of renewable energy technologies. The practical implications for politicians are recommendations for a funding scheme tailored towards the resources of renewable energy firms and therefore an efficient usage of public money.

In Section 2, I introduce the RBV with a focus on financial resources. In Section 3, I detail the research design, the data collection process and describe the variables. I present the results of my analysis in Section 4 and discuss the implications in Section 5.

2.2 Theory and Hypotheses

2.2.1 RBV as a Theoretical Foundation to Explain Superior Firm`s R&D Performance through Heterogeneous Financial Resources

The core question of our paper is whether and how public R&D funding as a specific financial resource affects a firm`s R&D performance. The widely recognized Modigliani-Miller theorem (Modigliani and Miller, 1959, 1961) claims that a firm’s financial structure should not affect its

R&D investments; however, asymmetric information and moral hazard between the inventor and investor as well as tax considerations reflect the practical limitations of the theorem (Hall and Lerner, 2010). We base our argumentation on the RBV, as it gives clear guidance on how to evaluate distinctive firm resources and to explain superior firm performance.

Penrose (1959) laid the foundations for the RBV by defining a firm as a bundle of resources and emphasizing their heterogeneity. Wernerfelt (1984), Barney (1986, 1991) ,and Dierickx and Cool (1989) applied this idea to the question of how firms can generate competitive advantage and why their performance differs. Despite the lack of a conclusive definition in the literature, we define resources as tangible and intangible assets that enable a firm to implement its strategy (Barney and Arikan, 2006). Tangible resources consist of financial assets (e.g., equity, debt, and retained earnings) and physical assets (e.g., buildings, equipment, machines). Intangible resources are related to a firm`s human capital (e.g., knowledge, skills, relationships) and organization (e.g., reputation, culture, internal reporting structures) (Barney and Arikan 2006). This internal strategy focus of the RBV stands in stark contrast to the external perspective of “Porter`s Five Forces Model” (Porter, 1979), which explains a firm`s strategy in the context of its surrounding industry characteristics. Decisions under uncertainty, a rapidly changing external environment, fading industry boundaries, and the importance of knowledge, organization and culture are arguments in favour of the RBV and against primarily static environmental models.

Dosi (1988) was one of the first scholars to apply this shift from an external towards an internal perspective to firm-level innovation. Inventions are not per se the result of external influences and industry characteristics, nor do they occur by evaluating competitor`s technology base and potential market opportunities. Instead, a firm`s resources are a critical source for innovation. Among these resources, Dosi (1988) and further scholars (e.g., Del Canto and González, 1999; Grant, 1996) highlight the important role of knowledge in explaining the heterogeneity of a firm`s R&D performance, while the role of financial resources is of minor relevance. We, however, apply criteria from the RBV to evaluate a resource (Barney, 1991; Barney and Arikan, 2006) in the next section and show that public R&D funding does have the potential to explain differences in R&D performances.

2.2.2 Absolute Monetary Value of Public R&D Funding

Public R&D funding is rare among competing firms as the public R&D budget is limited and the demand for R&D grants exceeds the supply (Bronzini and Iachini, 2014; Howell, 2016). It is non-substitutable in the sense that other financial sources are less cost-efficient than a public R&D grant. Besides the costs for the grant application and project documentation, there are no additional capital costs to compensate financiers for project risks and information asymmetries. It is imperfectly imitable as only few competitors fully recognize its role in the innovation process and, secondly, fulfil the funding conditions. It is inelastic in supply as an additional demand for R&D grants does not lead to an additional supply. Arguments for why public R&D funding is a valuable resource refer to (a) R&D personnel, (b) R&D working conditions, (c) R&D project portfolio, and (d) a firm`s reputation. Public R&D funding enables a firm to not only hire more R&D personnel but also to attract better-qualified scientists. Examples of how public R&D funding materializes for R&D working conditions, include better-equipped laboratories, enhanced stocks of raw materials, and improved access to databases, amongst others. In terms of the R&D project portfolio, the public nature of grants should enable innovation managers to invest in riskier R&D projects due to lower personal career risks (Aghion et al., 2013) and relatively low capital costs. In addition, public R&D funding facilitates market-based financing (Takalo and Tanayama, 2010) and in the case of early stage grants, raise the probability of venture capital investment (Howell, 2016) as the grant itself reduces the required credit amount and implies good project quality, both of which lower the risks for financiers. Public R&D funding increases a firm`s reputation and its institutional network, which facilitates national and global R&D cooperation with research institutes, suppliers, and competitors.

While previous studies add empirical evidence to our argumentation, they focus primarily on the manufacturing sector. For example, Bérubé and Mohnen (2009) find evidence for the positive effect of R&D grants for Canadian manufacturing and logging plants, which also benefit from R&D tax credits. Their survey-based analysis shows that funded firms produce more and better product innovations and are more successful in commercializing them. One of the very few studies based on real grant data for Germany shows a positive effect of public R&D funding on R&D expenditures for the German manufacturing sector between 1992–2000 (Hussinger, 2008). Her two step selection model shows that besides funding and past innovation activity, firm size and location are the most important variables to affect R&D performance. However, these firm-level insights from the manufacturing sector cannot be directly transferred to the energy sector for three reasons. First, a critical evaluation of public R&D funding in the renewable energy sector has to take into account the additional benefits for society and the environment due to the reduced carbon emissions. Second, renewable energy technologies have long-term development cycles and are not competitive at the beginning of their technology life-cycle due to learning and scaling disadvantages as well as a limited demand and thus require public support (Kahouli-Brahmi 2009; Grübler et al. 2012; Olmos et al. 2012; Bointner 2014). Third, a stable and economical energy system is at the core of a nation`s economy and therefore of special interest to the public (United Nations, 2015).

Previous studies on public funding in the energy sector mainly concentrated on the macro-level. For example, Johnstone et al. (2010) find a significant positive effect of public R&D funding for the wind and solar sector by using aggregated national patent and funding data for 25 countries between 1978-2005. Polzin et al. (2015) use a similar approach and highlight a positive effect of public R&D funding for the solar sector, but not on a significant level for the wind sector.

Although, there is substantial empirical evidence for our argumentation, a current meta-regression of 52 studies draws a heterogeneous picture of the effectiveness of public R&D funding (Dimos and Pugh, 2016). Their findings reject crowding out of private investments by public R&D funding but do not fully support additional R&D activity. Bronzini, Iachini (2014) also list mixed results on the effect of public R&D grants.

Taking these divergent empirical results into account, we adhere to our previous argumentation and the existing empirical evidence for a positive relationship between public R&D funding and R&D performance:

H1a: *Public R&D funding has a positive effect on the number of developed patents (quantitative indicator of R&D performance).*

H1b: *Public R&D funding has a positive effect on the average number of citing patents per patent (qualitative indicator of R&D performance).*

2.2.3 Past Funding Intensity

In addition to the absolute amount of public R&D funding, we analyze its longitudinal effect. Firms that received public funding over a longer period in the past benefit from a supplementary financial stability to implement additional and presumably riskier projects (Aschhoff, 2009). Furthermore, they build up a higher reputation to attract better scientific personnel and a closer institutional network. Longer and continuous R&D funding guarantees a periodic and formal project evaluation and reveals its importance to the employees, which ensures a better usage of resources (Oliver, 1997). Finally, there is empirical evidence (Afcha, 2012) that public R&D funding not only affects a specific R&D project, but also has a positive impact on a firm`s overall organization in the long run. Therefore we conclude:

H2a: *A higher past funding intensity has a positive effect on the number of developed patents (quantitative indicator of R&D performance).*

H2b: *A higher past funding intensity has a positive effect on the average number of citing patents per patent (qualitative indicator of R&D performance).*

2.2.4 Firm`s Overall Financial Situation

The arguments for a positive relationship between public R&D funding and R&D performance also hold true for a firm`s overall financial situation. Furthermore, a healthier financial situation enables the attraction of better-qualified scientists through higher wages, bonus payments, and additional incentives such as company cars, improved working conditions, and intense recruitment. Financially strong companies are in a position to establish dedicated patent departments that facilitate the costly, bureaucratic, and time-intensive patent application process. Soft factors of financial strength are sophisticated trainings, the establishment and monitoring of standardized innovation processes, the implementation of internal awards to raise employee`s motivation, and an R&D culture that allows early failures and concentrates on long-term success (Clancy and Moschini, 2013; Manso, 2011). In terms of the R&D project portfolio, a critical amount of financial resources allows innovation managers to expand their search activities and run riskier R&D projects (Chen and Miller, 2007), which have potentially higher technological and economic relevance. Finally, a higher ratio of internal funds promotes a firm`s innovativeness as it inhibits information drains on new inventions and reduces the dependency on bondholders, who tend to reduce their investment risks (Del Canto and González, 1999).

Empirical evidence supports our argumentation. For example, Alessandri and Pattit (2014) verify that a healthy firm`s overall constitution promoted R&D expenditures for a sample of 573 publicly traded U.S. manufacturing firms. The results from Ramana et al. (2015) indicate that financially strong renewable energy start-ups supported by venture capital focus on more experimental R&D projects and therefore develop more novel patents and have higher patent citation rates than incumbent firms, which focus on incremental innovation.

Given the above arguments and the empirical evidence, we conclude the following two hypotheses on a firm`s overall financial situation.

H3a: *A firm`s overall positive financial situation has a positive effect on the number of developed patents (quantitative indicator of R&D performance).*

H3b: *A firm`s positive overall financial constitution has a positive effect on the average number of citing patents per patent (qualitative indicator of R&D performance).*

2.3 Research Design

2.3.1 Sample and Data Collection

Our data consists of four distinctive databases that give unique and comprehensive insights on the German PV and wind sectors and the public R&D funding scheme. From these we build a sample of 1,448 firms (596 PV firms, 852 wind firms) for the years 2006–2015. The first step of our data collection approach was to identify the relevant players in the German PV and wind sectors for technology development. As no established firm database exists, we conducted intense research in business directories, insolvency registers and in the press. In a second step, we matched the firm names with the data sources DAFNE (Bureau van Dijk) and HOPPENSTEDT, which contain financial and general firm data (such as location, founding year, number of employees, key financials) for the last 10 years. We added additional information from corporate websites to improve the data quality. Hereby, we obtained the necessary data for the independent variables *equityratio* and *totalassets* as well as for the control variables *age*, *legal form*, and *zipcode.*

In a third step, we matched the firm names with the Derwent Innovations Index to obtain the patent application and citation data for the two dependent variables *number of patents* and *average number of citing patents per patent* as well as for the independent variable *patentstock.* The Derwent Innovations Index contains patent information from 40 global patent offices dating back to 1963. We use a search string of relevant technological keywords as well as the corresponding IPC classifications from previous studies (Huenteler et al., 2016; Johnstone et al., 2010; Popp et al., 2011) in order to only include highly relevant patents for the PV and wind sectors. This led to 1,716 PV and 2,175 wind patent applications for 2006–2015. We decided to use the priority date as it is closest to the time of invention (Braun et al., 2011; Dernis and Guellec, 2002). Finally, we entered the patent numbers into the European Patent Office database and downloaded 8,522 citing patents for the PV and wind sectors, which results in the variable *avg citing*.

To obtain the required funding information for the independent variables *grantamount* and *grantpercentage*, we matched the firm names with the public R&D funding data of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (period 1977 to 2013) and the German Federal Ministry for Economic Affairs and Energy, which took over its role and provided the grant data for 2014 and 2015. Grants are paid out as a percentage (up to 50%) of the expected project expenditures and based on criteria such as the applicant`s qualification, the content fit with the Ministry’s technology focus, the project’s risks and costs as well as its technological, economic, and social relevance (Bundesministerium der Justiz und für Verbraucherschutz, 2014). We excluded funds for research institutes or public institutions to focus on private PV and wind firms. We assumed an equal distribution of funds over time. Given these restrictions, our final sample consists of 206 publicly granted R&D projects with a volume of approx. 235 Mio €.[4]

[4] Our larger historical dataset between 1977 and 2015 allows us to gain additional insights. It consists of 357 projects with a volume of 627.6 Mio € for the PV sector and 418 projects with a volume of 153.1 Mio € for the wind sector. The average PV funds have a value of 1.8 Mio € and a period of 4.0 years, while the wind funds are smaller on average (0.4 Mio €) and more long term oriented (9.0 years). The grant size of PV projects differs between 6.283€ and 51.5 Mio €, while wind projects vary between 2.015€ and 5.0 Mio €. The minimum grant period for both PV and wind is 1 year while the maximum period for PV projects is 10 years and 13 years for wind projects. There is a first peak of funding for the PV sector in 1983 with an annual amount of 22.6 Mio €, followed by a second peak in 1990 with 23.7 Mio € and a high of 34.0 Mio € in 2013. In contrast, the highest funding period for the wind sector is between 1995 and 1999 with values between 9.0 and 9.6 Mio €, followed by a decline until 2006 and a new increase until 2013 with a value of 8.4 Mio €.

2.3.2 Variables

2.3.2.1 Dependent Variables

To measure a firm`s R&D performance in a quantitative and qualitative manner, we developed two separate models. The dependent variable used to measure the quantitative R&D outcome is the number of patents, i.e., the number of a firm`s patent applications per given year (Model 1).

The dependent variable used to explore qualitative divergences (Model 2) is the average number of citing patents per patent. We ensured constant citing periods of 3 years for each patent (close to the average sample citation lag of 2.78 years), which guarantees that a patent from, for example, 2008 has the same probability of being cited as a patent from 2011(Battke et al., 2016; Nemet, 2012) . Consequently, our patent sample is reduced to the years 2006–2012 while the citation data is from 2006–2015. In a second step, we divided the overall number of citing patents from a firm`s patent stock for a given year by the overall number of a firm`s patents for the same year. The underlying assumption for this qualitative assessment is that patents with a high technological value are more often cited by other patent applicants and examiners (Hall et al., 2001, 2005; Karki, 1997; Trajtenberg et al., 1997; Wartburg et al., 2005).

Critics of measuring a firm`s R&D performance via patent analysis refer to the missing patentability of certain inventions and biases through different national patent policies (Griliches, 1990) as well as a focus on invention rather than innovation. Firm strategic motives to patent (Blind et al., 2006), as well as the inclusion of irrelevant patents and exclusion of relevant patents (Johnstone et al., 2010) might also limit the research quality. We account for the latter limitation through detailed patent search strings built on patent classifications and relevant keywords (Popp

2005; Johnstone et al. 2010). In addition, patent analysis is an established research method (Griliches, 1990; Jaffe et al., 1993) that enables public access to a granular level of information for various countries over a long time horizon (Dernis and Guellec, 2002; Hall et al., 2001). It also exceeds R&D input factors such as R&D expenditures or personnel as they document the result of the R&D process (Jaumotte and Pain, 2005; Johnstone et al., 2010).

2.3.2.2 Financial Resource Variables

We take the annual amount of public R&D funding in Euro that a firm receives (*grantamount*) to test the effect of public R&D funding on R&D performance (Hypotheses 1a and 1b). The percentage of years a firm received at least one public grant between 1977 and 2005 (*grantpercentage*) allows us to measure the time-effect (Hypotheses 2a and 2b). To operationalize a firm`s overall financial situation, we use the *equity ratio*, i.e., the ratio of a firm`s equity in Mio Euro and its total assets in Mio Euro. A higher equity ratio means a healthier overall financial situation (Hypotheses 3a and 3b).

2.3.2.3 Other RBV Variables and Control Variables

We examine firm size in terms of total assets in Mio Euro (*total assets*), which serves as an indicator of physical resources. Arguments for a positive relationship between firm size and R&D performance include economies of scale in R&D, more and better qualified R&D personnel, the possibility to diversify the R&D project portfolio as well as dedicated R&D departments and standardized innovation processes streamlined to patent applications. For larger firms, patent applications also serve as an innovation performance indicator to evaluate research work, allocate R&D budgets, and structure R&D organizations. Strategic motives to patent such as reputation, licensing incomes, blockade of competitors, and better negotiation power are also more relevant for larger firms (Blind et al., 2006).

We analyze the accumulated technological knowledge base of a firm and hereby account for an intangible resource of the RBV. This knowledge base is reflected in a firm`s *patent stock*, which is the depreciated number of previous patents between 1977 and 2005. The depreciation rate is set to 0.15, which is in line with knowledge literature (Aerts and Schmidt, 2008; Hussinger, 2008; Jaffe, 1986). We depreciate the values for *patentstock* until 2005 and keep them stable to reduce endogeneity to a minimum.

We control for a firm`s age for two contrary reasons. On the one hand, younger firms might grant fewer patents due to additional resource constraints and might be less cited due to a lower reputation level. On the other hand, patents play a more important role for younger firms than for established ones in their quest to be successful in the marketplace (Griliches, 1990). Younger firms might also pre-select the most technologically and economically valuable inventions due to the high costs and efforts of the patent application process, which should lead to a higher number of citing patents per average patent. Due to different industry structures and technology-lifecycles, we control for sectoral divergences between the PV and wind sectors using a binary variable (PV=0; Wind=1). Furthermore, we control for firm location using the first digit of the zip-code (0-9) as structural differences in Germany might influence a firm`s R&D performance and the distribution of public R&D funding (Aerts and Schmidt, 2008; Czarnitzki and Fier, 2003; Hussinger, 2008). Finally, we control for a firm`s legal form due to different stakeholder and shareholder influences, financing opportunities as well as legal requirements.

2.3.3 Models

Poisson regression and negative binomial regression models are the most common models for count data (with a certain amount of zero outcomes) such as patent data (Drivas and Economidou, 2015; Johnstone et al., 2010). While the Poisson regression assumes that the conditional mean equals the variance, the negative binomial regression is less restrictive and allows the conditional mean and variance to vary (Hausman et al., 1984). Given the empirical evidence for overdispersion, we use a panel negative binomial regression model to test our hypotheses for patent count (Model 1). We run a GLS random effects panel regression model for patent quality (Model 2) as the average number of citations per patent is non-count outcome.

The unit of analysis for both models is firm level and the analysis period is 2006–2015. Our analysis observes a period of up to 3 years after the first funding payment as it is unclear when public R&D funding "materializes" into the form of a patent application. A previous study of the Japanese PV sector shows a time lag for R&D expenditures of 2.8 years (Watanabe et al., 2000), which is in line with other studies for the PV and wind sectors (Klaassen et al., 2005; Kobos et al., 2006).

2.4 Results

2.4.1 Results Model 1: Patent Count as Dependent Variable

Model 1 shows the effect of the described variables on firm-level R&D performance in a quantitative manner using patent count as the dependent variable (Hypotheses 1a, 2a and 3a).

Tables 4 and 5 provide the descriptive statistics and correlation matrix. The number of patents per firm (*patent*) is highly correlated with *patentstock* representing a firm`s technology knowledge base (r=0.80). All other correlations have low values, except *totalassets* and *patentstock* (r=0.54).

	Variable	N	Mean	S. D.	Min	Max
1	Patent	14,480	0.27	3.88	0.00	255.00
2	Grantamount	14,480	16,202.27	160,095.80	0.00	9,159,941.00
3	Grantpercentage	14,480	0.07	0.12	0.00	0.85
4	Equityratio	7,121	0.37	0.27	0.00	1.00
5	Totalassets	7,122	692.67	4,914.91	0.00	71,763.20
6	Patentstock	14,480	0.23	3.89	0.00	138.98
7	Age	11,352	28.95	32.73	1.00	186.00
8	Sector	14,480	0.59	0.49	0.00	1.00
9	Zipcode	14,200	4.32	2.73	0.00	9.00
10	Legalform	14,280	1.98	1.60	1.00	6.00

Table 4: Descriptive Statistics of Model 1 with Dependent Variable *number of patents*

		1.	2.	3.	4.	5.	6.	7.
1	Patent	1						
2	Grantamount	0.32	1					
3	Grantpercentage	0.07	0.21	1				
4	Equityratio	-0.00	0.01	-0.03	1			
5	Totalassets	0.41	0.14	0.15	-0.04	1		
6	Patentstock	0.80	0.21	0.09	-0.01	0.54	1	
7	Age	0.15	0.03	0.06	0.02	0.28	0.20	1

Table 5: Correlation Matrix of Model 1 with Dependent Variable *number of patents* (N=7,085)

The empirical result of Model 1 (see Table 6) fully supports Hypothesis 1a; *grantamount* has a highly significant (p-value < 0.01) and positive effect on the *number of patents*. The annual amount of public R&D funding does have a positive impact on a firm`s patent activity.

For Hypothesis 2a, the independent variable *grantpercentage* shows the expected positive sign at a highly significant level (p-value < 0.01). This result provides evidence that firms with long-term public support produce a higher number of patents than their peers.

We find limited but substantial support for Hypothesis 3a as the independent variable *equity ratio* has a positive sign for all lags, but only at a significant level for lags 2 and 3. This indicates that a healthier firm`s overall financial situation leads to a higher R&D performance in terms of patent output.

The results for our control variables provide additional insights. First, firm size measured by *totalassets* has no significant effect on a firm's R&D performance. Second, a firm's technology knowledge base *(patentstock)* has a highly significant and positive effect on the *number of patents*. Third, patent activity decreases with a firm`s *age* at a significant level. Fourth, the binary variable *sector* shows that wind firms produce significantly less patents than PV firms.

	No lag	**f1 lag**	**f2 lag**	**f3 lag**
Grantamount	5.94e-07***	4.30e-07***	3.29e-07***	6.17e-07***
	(9.59e-08)	(1.16e-07)	(1.26e-07)	(2.27e-07)
Grantpercentage	1.922***	2.187***	2.228***	2.035***
	(0.591)	(0.582)	(0.602)	(0.639)
Equityratio	0.214	0.106	0.380*	0.472**
	(0.209)	(0.208)	(0.216)	(0.222)
Totalassets	1.28e-05	5.90e-06	2.38e-06	-4.07e-06
	(1.28e-05)	(1.26e-05)	(1.29e-05)	(1.33e-05)
Patentstock	0.0241***	0.0232***	0.0249***	0.0337***
	(0.00601)	(0.00614)	(0.00641)	(0.00720)
Age	-0.00580**	-0.00620**	-0.00513**	-0.00754***
	(0.00244)	(0.00244)	(0.00253)	(0.00268)
Sector	-0.796***	-0.859***	-0.873***	-0.898***
	(0.140)	(0.140)	(0.145)	(0.147)
Constant	-1.140***	-1.009***	-1.115***	-0.991***
	(0.224)	(0.220)	(0.226)	(0.229)
N	7,085	7,067	6,637	5,902
Number of firms	1,022	1,022	1,021	1,017
Log likelihood	-1,978.12	-2,028.71	-1,926.91	-1,780.03
Prob > chi2	0.0000	0.0000	0.0000	0.0000

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 6: Estimated Coefficients of the Negative Binomial Regression Analysis for Model 1 with Dependent Variable *number of patents* as Quantitative Indicator for R&D Performance and a Time Lag from Zero to Three Years

Note: The control variables *legal form* and *zipcode* are included in the model but not listed here.

2.4.2 Results Model 2: Average Number of Citing Patents per Patent as Dependent Variable

Model 2 shows the effect of the outlined variables on the firm level R&D performance in a qualitative manner using the average number of citing patents per patent as the dependent variable (Hypotheses 1b, 2b and 3b).

Tables 7 and 8 provide the descriptive statistics and correlation matrix. In contrast to Model 1, *avgciting* is not highly correlated with *patentstock*. Only the variables *totalassets* and *patentstock* are highly correlated (r = 0.54).

	Variable	N	Mean	S. D.	Min	Max
1	Avgciting	10,136	0.09	0.62	0.00	20.00
2	Grantamount	10,136	13,908.08	121,234.30	0.00	4,833,975.00
3	Grantpercentage	10,136	0.07	0.12	0.00	0.85
4	Equityratio	5,936	0.36	0.26	0.00	1.00
5	Totalassets	5,937	635.22	4,661.31	0.00	71,763.20
6	Patentstock	10,136	0.23	3.89	0.00	138.98
7	Age	7,798	27.93	32.79	1.00	183.00
8	Sector	10,136	0.59	0.49	0.00	1.00
9	Zipcode	9,940	4.32	2.73	0.00	9.00
10	Legalform	9,996	1.98	1.60	1.00	6.00

Table 7: Descriptive Statistics of Model 2 with Dependent Variable *average number of citing patents per patent (avgciting)*

		1.	2.	3.	4.	5.	6.	7.
1	Avgciting	1						
2	Grantamount	0.08	1					
3	Grantpercentage	0.03	0.22	1				
4	Equityratio	0.04	0.00	-0.02	1			
5	Totalassets	0.08	0.06	0.15	-0.03	1		
6	Patentstock	0.14	0.07	0.09	-0.00	0.54	1	
7	Age	0.01	-0.01	0.06	0.02	0.28	0.20	1

Table 8: Correlation Matrix of Model 2 with dependent Variable *average number of citing patents per patent (avgciting)* (N=5,902)

Contrary to the results regarding patent count, we did not find support for Hypothesis 1b, which predicts that public R&D funding *(grantamount)* has a significantly positive effect on patent quality, except for lag 2 (see Table 9).

For Hypothesis 2b, there is no empirical evidence that firms receiving public R&D funding over a longer period of time *(grantpercentage)* produce patents with a superior technological and economic value.

In addition, *equityratio* has no significant effect on the number of citing patents, except for lag 3. Thus, there is only very limited empirical evidence for Hypothesis 3b and we conclude that a firm`s overall financial situation does not affect patent quality.

The results for the other independent variables of patent quality are in line with the results for patent count. Intuitively, the variable *patentstock* has a highly significant and positive value, which indicates that a firm´s technological knowledge base has a positive effect on a patent´s technological and economic relevance. Firm size *(totalassets)*, age, and location have no significant effect, while patents for wind firms are significantly less cited than patents for PV firms (*sector*).

	No lag	f1 lag	f2 lag	f3 lag
Grantamount	2.50e-07	6.96e-08	5.09e-07**	2.35e-07
	(1.64e-07)	(1.08e-07)	(2.04e-07)	(1.80e-07)
Grantpercentage	0.106	0.171	0.140	0.157
	(0.114)	(0.121)	(0.146)	(0.166)
Equityratio	0.0665	0.0392	0.0703	0.118*
	(0.0484)	(0.0425)	(0.0482)	(0.0653)
Totalassets	-3.76e-06	-2.38e-06	-1.45e-06	1.17e-06
	(4.06e-06)	(5.96e-06)	(7.64e-06)	(1.04e-05)
Patentstock	0.0193***	0.0197***	0.0203**	0.0196**
	(0.00685)	(0.00727)	(0.00844)	(0.00950)
Age	-0.000326	-0.000234	-0.000249	-4.45e-05
	(0.000415)	(0.000531)	(0.000641)	(0.000829)
Sector	-0.108***	-0.121***	-0.104**	-0.120**
	(0.0331)	(0.0367)	(0.0421)	(0.0481)
Constant	0.156***	0.188***	0.172***	0.195***
	(0.0566)	(0.0652)	(0.0652)	(0.0742)
N	5,902	5,121	4,254	3,372
Number of firms	1,017	999	982	962
Prob > chi2	0.0000	0.0000	0.0000	0.0000

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 9: Estimated Coefficients of the GLS Regression Analysis for Model 2 with Dependent Variable *average number of citing patents per patent (avgciting)* as Qualitative Indicator for R&D Performance and a Time Lag from Zero to Three Years

Note: The control variables *legal form* and *zipcode* are included in the model but not listed here.

Overall, the empirical results support Hypotheses 1a, 2a and 3a and do not support Hypotheses 1b, 2b and 3b. The absolute value of public R&D funding *(grantamount)*, the past funding intensity *(grantpercentage)*, and a firm`s overall financial constitution *(equityratio)* only have a positive effect on patent count but not on quality. Interestingly, a firm`s technology knowledge base affects both patent quantity and quality in a significant positive manner.

2.4.3 Robustness-checks

We conducted an OLS analysis for both models and examined the variance inflation factors (VIFs). All VIFs were clearly below the recommended threshold of 10 (Hair, 2010), thus rejecting multicollinearity as a potential problem (Model 1 max. VIF=3.31, mean VIF=1.65; Model 2 max. VIF=3.29, mean=1.67). For Model 1, we calculated a zero-inflated negative binomial regression model to account for the high number of zero count outcomes. Instead of time-lags for the patent data, we accumulated the number of patents for 1, 2, and 3 years in separate models. The results undermine the significant positive effect of a higher past funding intensity (support for Hypothesis 2a) and a firm`s technology knowledge base on the number of patents. For Model 2, we calculated a negative binomial regression model with rounded count outcomes instead of a GLS random-effects model. All the previous findings were confirmed, except that it does show a significant positive effect of a higher past funding intensity on patent quality (support for Hypothesis 2b). Finally, we used a firm`s sales data and the number of employees in separate models as a proxy for firm size instead of a firm`s total assets. Due to limited data availability, the sample size of these models is over 40% less than the base model using *totalassets*. Nevertheless, these models are in line with the above key findings regarding the initial hypotheses.

2.5 Conclusion

2.5.1 Summary of Main Results and Theoretical Implications

Our paper explores the relationship between public R&D funding and firm level R&D performance and draws thereby on a unique dataset of granular funding data, a firms` key financials as well as patent and citation data for the German PV and wind sectors. Our main objective is to contribute substantial insights on the effectiveness of innovation policy instruments by adding a firm-level perspective with the RBV as its theoretical foundation. Through financial resources at the core of our analysis, the key findings suggest that public R&D funding and a firm`s overall financial situation have a significant positive effect on patent count but have no effect on patent quality. This result is in contrast to our initial argumentation in Section 2.2 and we suggest three possible explanations. First, public funded R&D projects are well documented and made public upon completion. Therefore, innovation managers are forced to patent their inventions before this disclosure independent of whether the patent application process is necessarily worth the R&D project's value. While this increases the number of patent applications per firm, it also increases the number of "low value" patents among the funded firm`s patent stock, which decreases the average patent quality. Second, innovation managers may invest public R&D funding into fundamental research whose technological relevance manifests after a longer period. Third, examiners at the funding institutions might not be able to fully assess the technological relevance due to information asymmetries and then fund less valuable R&D projects.

Our results imply substantial contributions to linking research on firm-level innovation and RBV. First, we add an institutional perspective to the analysis of how financial resources influence a firm`s R&D performance by incorporating public R&D funding data. Second, the significant positive effect of a firm`s technology knowledge base on both patent count and quality emphasizes the importance of knowledge as an intangible resource. This result is intuitive as a larger knowledge base reflects better qualified R&D personnel as well as a certain amount of experience with or even incentive through patent applications. Previous studies (e.g., Del Canto and González, 1999; Galbreath, 2005) came to a similar conclusion, which consequently lead to a further development of the RBV towards the knowledge-based theory of the firm, as pioneered by Grant (1996). Third, the insignificant effect of firm size indicates that physical resources are of minor importance for explaining divergent R&D performances. Fourth, we provide empirical evidence that the evaluation of resources based on the RBV serves as an indicator of superior quantitative but not of qualitative R&D performance.

A second contribution of our research concerns the younger literature stream of energy innovation systems (Gallagher et al. 2006; Gallagher et al. 2012; Grübler et al. 2012). By analyzing the effects of public R&D funding on German renewable energy firms` innovation performance, we gain empirical evidence of institutional influences on firm-level innovation behavior. The policy and managerial implications in the next section give insights into one of its core research gaps: the relationship between institutions and actors.

2.5.2 Policy and Managerial Implications

Our findings draw a heterogeneous picture of the effectiveness of the current public R&D funding scheme for renewable energy technology in Germany as public R&D funding has a significant positive effect on patent count but not on patent quality. This empirical result emphasizes the need to adjust the current funding scheme to promote innovations with higher technological relevance and invest public money more efficiently. A possible implication for funding agencies to better examine the R&D proposals is a more transparent and detailed description of the future technological relevance and implications for the renewable energy industry and other sectors. In addition, funding agencies could re-evaluate the R&D projects after several years and allocate bonus-payments depending on patent citation data or the judgement of an external jury. Our findings suggest taking into account a firm`s previous number of patents during the funding selection process as firms with a larger technology knowledge base and patent experience *(patentstock)* tend to produce more and more valuable patents. We find no grounds for including a firm's size *(totalassets)* and only limited support for considering a firm`s age as a selection criteria for public funding.

Our results encourage innovation managers to apply for public R&D funding as it does have a direct and long-term positive effect on patent count. One possible explanation for the insignificant impact on patent quality might be the selection of the underlying R&D projects. Innovation managers might invest the public funds in fundamental research of less technological and economic value, which leads to a minor number of citations per patent. Based on previous studies (Manso, 2011; Tian and Wang, 2014), we see the risk-free and cost-efficient financial resource of public R&D funding as an ideal starting point to implement a failure-tolerant R&D culture and investment in uncertain R&D projects with high technological, economic, and social relevance. Finally, the significant positive effect of a firm`s technology knowledge base implies the need to constantly invest in R&D personnel and processes with a long-term perspective.

2.5.3 Limitations and Suggestions for Future Research

This paper includes some limitations, which leaves room for future research. First, intense data research provides insightful information on key determinants of a firm`s R&D performance, but we suggest the examination of further RBV variables, e.g. number and qualification of scientific personnel, equipment and IT systems in R&D laboratories, relationships to customers and suppliers to incorporate feedback during the innovation process. Internal R&D funds are of particular interest as their effectiveness could be compared to external (public) R&D funds.

Second, the focus of the patent analysis is primarily number- and not content-driven. Interdisciplinary research by economists and engineers could distinguish between product- and process-innovation, the degree of innovation, or various technological components (e.g., cell, module, grid connection, mounting system for PV; rotor, power train for wind) (Huenteler et al., 2016).

Having focused on financial resources in the context of RBV and public R&D funding, our results indicate that further research is needed on the importance of intangible resources as knowledge and organizational R&D structure for firm-level R&D performance (Nelson, 2009; Nemet, 2012). Czarnitzki et al. (2007) confirm a positive effect of public R&D funding in a collaborative rather than an isolated research environment for German and Finnish firms. Future analysis in this field should focus on intra-industry, inter-industry, and cross-border knowledge spillovers as well as different organizational R&D structures in order to maximize R&D outcome and adopt the funding criteria of current innovation policy. Patent and citation data are also a valuable source of information for this research area.

3. Paper 2: Firm Strategic Behavior in Response to Europe`s Renewable Energy Policy - A Cross-Country Analysis

3.1 Introduction

Governments worldwide are trying to solve the "energy trilemma" of secure, affordable, and environmentally friendly electricity provision. An appropriate incentive for incumbent energy utilities is central to the solution as they dominate the majority of the electricity value chain, control customer channels, and accumulate large knowledge bases, all of which enables them to steer technological progress (Geels et al. 2014; Jacobsson, Bergek 2004). Although energy incumbents are rather resilient to business model (BM) changes (Richter 2013; Shomali, Pinkse 2016), they do acknowledge that new energy laws and regulations are key drivers of change (Gsodam et al. 2015). Although a better understanding of how legal environment dynamics affect incumbent energy utilities' BMs is crucial for a successful energy transition, this is hardly reflected in scientific literature (Gallagher et al. 2012; Steen, Weaver 2017). Previous studies on BMs in the electricity sector focus on 'pure' renewable energy (RE) companies (Engelken et al. 2016; Gabriel, Kirkwood 2016) as well as the technological progress of decentralized energy solutions and an active customer role (Green, Newman 2017; Wainstein, Bumpus 2016; Strupeit, Palm 2016) rather than on incumbent firms. In the literature on incumbent energy utilities, researchers mainly outline static types of BMs (Richter 2012; Valocchi et al. 2014) or focus on single cases for specific environments (Engelken et al. 2016). To the best of my knowledge, only a few researchers conduct a cross-country analysis (Stenzel, Frenzel 2008; Strupeit, Palm 2016; Helms 2016), despite the fact that the literature emphasizes the importance of different national contexts (Kern, Markard 2016).

I contribute to furthering theory development as this paper differs from previous studies in four dimensions. First, I shift the research focus to incumbent firms rather than start-ups or new market entrants. Second, I apply a dynamic instead of a static BM perspective. Third, I discuss a cross-country analysis in order to account for different national energy policies. Thus, I enrich the scientific discussion, which is dominated by single-case studies. Finally, I focus on legal rather than technological environmental changes, which has been neglected in previous studies. My research question is consequently: How have European incumbent energy utilities adjusted their BMs in response to changing environmental dynamics caused by new energy laws and regulations? To answer this question, I develop a multiple case-study-analysis (Yin 2009) for the legal environment of the French, UK, and German electricity markets and their main incumbent energy utilities Électricité de France SA (EDF), Scottish and Southern Energy plc (SSE) and E.ON SE (E.ON). The observation period of 2009–2017 allows me to account for the Fukushima accident in 2011. The implications of this disaster for energy incumbents have received only limited research attention (Kungl 2015). The theoretical foundation is the contingency framework on BM dynamics put forward by Saebi (2015), which I combine with the Business Model CANVAS (Osterwalder 2004; Osterwalder, Pigneur 2011). Documents from national governments, national regulatory bodies, Ministries for Energy and Economy, the International Energy Agency, and Eurostat are the source of the data on national energy laws and legislation and market characteristics. BM changes are documented based on annual, financial, and sustainability reports; corporate websites; company profiles; and analyst statements (Hoover's, MarketLine, Factiva) as well as semantic search strategies in financial newspapers (via Factiva).

Given the limitations of case-study design and the respective small number of observed sample firms, all results have to be interpreted cautiously. My results thus represent rather options, indications and possibilities rather than verified tests and proves of theories. One of the first results satisfies the theoretical expectations of Saebi's (2015) contingency framework. The French incumbent EDF, which is in a constant legal environment, develops its BM naturally and gradually, with only an incremental radicalness; the British SSE, which is in a more dynamic environment, permanently aligns its BM to the environment; and the German E.ON, which is challenged by a fundamental shift of its legal environment, implements the most radical and widespread BM changes, including the organizational split of its conventional business power and trading unit Uniper. The second key result is a first identification of major BM trends existing independently of legal environmental dynamics. For all three incumbents, I observe a broader value proposition including energy services, a higher customer-orientation with digital channels, the increasing relevance of RE within the generation portfolio and a shift towards regulated business.

The main theoretical contribution of this paper is the discussion of the contingency framework on BM dynamics put forward by Saebi (2015). I find first indications that her theoretical expectations might hold true for the analyzed energy utilities. This is very interesting because the BM elements of incumbent energy utilities differ from other sectors. The value proposition shifts from commodity provision to energy-related services (e.g., smart meter reading, smart home applications, e-mobility), but is still based on electricity, the product properties of which are hardly differentiable to end-customers. The BM element infrastructure management is long-term-orientated as it includes power plants with a lifetime of over 50 years. The customer interface changes from a passive consuming to a more active prosumer role. Finally, financials are restricted to deregulated and regulated businesses. In addition, incumbent energy utilities were under no pressure to innovate their BM over decades due to oligo- or monopolistic structures. It was thus motivating to examine whether their willingness and capability to change corresponds to Saebi's theory. A second theoretical contribution is a better understanding of how institutions influence the (BM) innovativeness of incumbent energy, which is a key research gap in energy innovation systems (Gallagher et al. 2012). Potential implications for policy-makers include the call to communicate new laws early on and align them closely with the industry. A summary of BM trends and guidance on effective BM changes for different environmental dynamics are beneficiary for European utility executives as it addresses one of their top strategic priorities (IDC Energy Insights 2015).

In Section 2, I provide a comprehensive introduction to research on BM and then explain the case study design and data collection in Section 3. Section 4 consists of the within-case analysis for the three sample electricity markets and incumbents. Within Section 5, I provide the cross-case analysis and conclude in Section 6 with theoretical contributions, practical implications, limitations and further research.

3.2 Theoretical Background

3.2.1 Definition of a BM and its Interlinkages with Strategy

I base this paper on the close links between BMs and strategy and understand a BM as a concrete and structured blueprint for achieving the long-term goals defined in a firm`s strategy (Casadesus-Masanell, Ricart 2010; Gsodam et al. 2015). Thus, BM changes directly reflect a firm`s strategic response to its environment. BM concepts evolved with the emergence of IT business in the 1970s

(Stähler 2002) and developed further with electronic commerce and the new economy in the late 1990s (Magretta 2002; Osterwalder 2004). The growing acceptance of BMs can be attributed to the shortcomings of classical management theories in explaining the fundamental changes to entire industries through new digital technologies (Amit, Zott 2001). In order to capture this complexity better, the very form of a BM corresponds to an “abstract conceptual model” (Osterwalder 2004, p.15), a “coherent framework” (Chesbrough, Rosenbloom 2002), “logic” (Chesbrough, Rosenbloom 2002; Schallmo 2013), an “abstract representation ” (Al-Debei et al. 2008, p. 8), or a “conceptual tool” (Weiner et al. 2010, p. 23). Although the literature on BMs is fragmented (Zott et al. 2011; Schallmo 2014; Ramin 2017, see Table 3 in the Introduction), a common understanding of a BM is that it describes how a firm creates, delivers, and captures value (Amit, Zott 2001; Teece 2010; Osterwalder, Pigneur 2011). Based on this view, Osterwalder developed the BM Canvas (Osterwalder 2004; Osterwalder, Pigneur 2011), which is a structured framework for conceptualizing BMs. According to the BM CANVAS (Osterwalder 2004; Osterwalder, Pigneur 2011), a BM has four pillars: *value proposition*, *customer interface*, *infrastructure management*, and *financials*. *Value proposition* is the sum of products and/or services that create value for distinctive customer segments by satisfying needs. It is the basis for a firm`s future revenues, the rationale for its costs, and is at the core of its operations. *Customer interface* defines target customers as well as channels for reaching and communicating with them in order to build a certain kind of relationship. *Infrastructure management* explains how value is created through a bundle of required tangible and intangible assets, key activities, and a network of partners. *Financials* represent the ratio between the costs to create value and the generated revenue.

3.2.2 Dynamic View on BM Change

Although scholars highlight the importance of changing BMs over time due to new customer needs, technologies, legislation (Teece 2010), or internal factors (Demil, Lecocq 2010), static rather than dynamic studies on BMs dominate the current scientific discussion (Ramin 2017). One of the few exceptions is the contingency framework on BM dynamics put forward by (Saebi 2015). She distinguishes three different archetypes of BM changes (*evolution*, *adaptation*, and *innovation*) along five criteria (planned outcome, scope of change, degree of radicalness, frequency of change, degree of novelty). *BM evolution* consists of minor changes to the existing BM along a natural trajectory to realize efficiency gains. Only a few BM elements are affected, the degree of radicalness is incremental, and the BM changes occur gradually. *BM adaptation* also entails changes to the existing BM, but with a possibly larger scope and a higher degree of radicalness and frequency. In contrast to BM evolution, the changes do not occur along a firm`s natural trajectory but rather as a conscious reaction to varying external settings and the planned outcome to attain alignment with the environment. *BM innovation* is a radical and extensive change to the existing BM or the creation of a new BM as a separate unit. According to Saebi (2015), the planned outcome is a disruption of market conditions.

The theoretical underlying causes of these three archetypes are the three environmental dynamics *regular change*, *environmental competitiveness*, and *environmental shift*. *Regular changes* are highly predictable deviations from the status quo with a limited scope and pace. Within the context of regular changes, firms tend to follow the logic of BM evolution and execute marginal adjustments to their existing BM. Characteristic of *environmental competitiveness* is the permanent transition of external conditions within moderate boundaries. It forces firms to exhibit a high degree of flexibility and a careful use of resources, which makes BM adaptation the most suitable alternative. *Environmental shifts* are neither predictable nor frequent, but result in substantial changes in a firm`s environment. Consequently, Saebi (2015) favors BM innovation in response to environmental shifts.

In summary, Saebi’s contingency framework systematically links environmental dynamics with BM changes based on five criteria and breaks down the fragmented term "BM change" into *BM evolution, adaption,* and *innovation.* It thus serves as the theoretical foundation for this paper. A minor limitation is the unclear definition of the “disrupt market conditions,” which Saebi claims is the planned outcome of *BM innovation* (Saebi 2015, p. 151). To remedy this, I suggest the planned outcome of *BM innovation* is to proactively establish a fundamental new definition of market conditions through changes in the existing BM or the creation of a distinctive new BM as a separate unit instead of to “disrupt” market conditions in the sense of Christensen (2006). Table 10 shows this adjusted version.

Archetype of BM change	**BM evolution**	**BM adaptation**	**BM innovation**
Planned outcome	Natural, minor adjustments of existing BM to increase operational efficiency	Align existing BM with the environment	Proactively establish a fundamental new position to and definition of market conditions through changes in existing BM or creation of a distinctive new BM for a separate unit
Scope of change	Narrow	Narrow-wide	Wide
Degree of radicalness	Incremental	Incremental-radical	Radical
Frequency of change	Continuous, gradual	Periodically	Infrequently
Degree of novelty	Not applicable	Novelty is not a requirement	Must be novel to the industry
Environmental dynamic	Regular change	Environmental competitiveness	Environmental shift

Table 10: Adjusted Version of Saebi`s Contingency Framework for BM Changes and Environmental Dynamics (Saebi, 2015)

3.3 Methodology and Data

3.3.1 Research Design and Data Collection

I chose a multiple case-study approach to discuss Saebi's (2015) contingency framework for three reasons (Yin 2009). First, the research question aims to analyze how legal environmental dynamics influence an energy incumbent`s BM. Second, I, as the investigator, have limited control over the phenomenon, i.e. the influence of energy policy on incumbent energy utilities' BMs. Third, it is a contemporary phenomenon within a real-life context, the boundaries of which are not entirely obvious. The context of each case is the environmental dynamics represented by the main laws and regulations affecting the different electricity markets. The unit of analysis is the BM changes of the incumbent energy utilities. The observation period is 2009–2017 in order to include the implications of the Fukushima accident in 2011 for national energy policies and utilities' BMs. BM changes refer to the original "pre-Fukushima BM" based on data from 2009 and 2010. Following (Bieger, Reinhold 2011), the research design can be classified as universal and dynamic since it discusses the entire BM, with a focus on BM changes over a distinctive period. To guarantee comparability between the sample firms, construct validity, and reliability, the BM elements were pre-defined based on the BM CANVAS (Osterwalder 2004; Osterwalder, Pigneur 2011) for a vertical-integrated energy utility incumbent (Richter 2013; Gabriel, Kirkwood 2016; Strupeit, Palm 2016; Löbbe, Hackbarth 2017). I explicitly focus on the activities in their domestic markets to account for the specific legal environment.

I set up two distinctive databases for (a) environmental dynamics and (b) BM changes in order to comply with the guiding principles for case-study design (Yin 2009) and, above all, to achieve process transparency, objectiveness, and a critical judgement of data sources and data triangulation. For (a) environmental dynamics, I based the information on data from national governments, national regulatory bodies Ministries for Energy and Economy, the International Energy Agency, and Eurostat for the sample countries France, the UK, and Germany. For (b) BM changes, I used annual, financial, and sustainability reports, as well as corporate presentations and websites, company profiles, and analyst reports as primary sources of information (Hoover’s, MarketLine, Factiva). In addition, I applied semantic search strategies in business and financial newspapers (via Factiva).

3.3.2 Sampling

I selected the electricity markets of France, the UK, and Germany as they represent the three different types of environmental dynamics and also share the required similarities to allow comparability. The list of similarities includes their commitment to upholding European Energy laws following the Lisbon Treaty in 2007, their geographic embeddedness in the European market as well as similar customer needs and a comparable deployment level of fossil, nuclear, and RE technologies. Finally, they represent the three largest European markets. With respect to the environmental dynamics, I focus on national energy legislations and briefly outline their implications on competition. Applying the criteria for environmental dynamics identified by Saebi (2015), the French electricity market corresponds to the environmental dynamic regular change. The frequency, amplitude, and velocity of legal changes within the French energy policy are low and their predictability is high. This is because the French government owns 85.6% of EDF and protects its dominating market position, which is reflected in the market share of 87.3% for residential customers and 65% in the business and local authorities segment at the end of June

2017. It is thus historically resilient to policy changes, the adaptation of international climate protection agreements, and the liberalization of the domestic energy market (Andriosopoulos, Silvestre 2017). As an example for this resilient political behavior, the French unbundling process of its transmission network was only realized in 2000 and of its distribution network in 2008, i.e. years later than in other European countries, and both unbundled firms are still wholly-owned subsidies of EDF (Andriosopoulos, Silvestre 2017). In 2010, the EDF was legally bound by the Act for New Organization of the Electricity Market (Nouvelle Organisation du Marché de l'Électricité) to sell 25% of its annual nuclear production to an alternative supplier for a fixed price, which led to a tendency towards more competition long after other European countries. While the Fukushima accident in 2011resulted in stress tests and safety upgrades for all nuclear power plants, it did not lead to a substantial political shift in France. Further proof for regular change is found in the lifetime extension for nuclear power plants from 40 to 50/60 years, the comparatively low roll out of smart meters, the postponement of hydropower concessions for a broader range of firms, and the current degree of interconnectedness with other European electricity markets, which is clearly below the initial target (International Energy Agency 2017). Only recently, the Energy Transition and Green Growth Act limited the share of nuclear power to 50% in 2025, set ambitious RE targets of 23% of final energy consumption in 2020, and included a carbon price trajectory as well as a market premium system and tenders for RE to promote cost-efficiency. Finally, regulated tariffs for large and medium-sized industrial customers have been abolished and only started to be phased out for private customers in 2016. These gradual, slow, and predictable regulative changes also lead to a stable competitive environment. EDF and Engie are the only two players with a market share of over 5% and jointly controlled over 86% of the French retail market and 92% of electricity generation (EDF alone 86%) in 2015. Enedis, an EDF subsidiary, holds 95% of all distribution network concessions and thus hinders competition (International Energy Agency 2017).

In contrast, the UK electricity market corresponds to the environmental dynamic environmental competitiveness as new energy laws and regulations are becoming effective at substantial frequency in a predictable manner with a moderate amplitude, resulting in substantial operational freedom for the energy incumbents. In the 1980s and with the Electricity Act of 1989, the UK electricity market was one of the first to undergo liberalization, deregulation, and privatization (Renn, Marshall 2016), which resulted in a fully open electricity market in 1999. In this tradition, key legislations affecting the observation period such as the Energy Acts of 2010, 2013, and 2016 as well as the Climate Change Act of 2008 focus on greenhouse gas reduction through a broad, primarily technology-neutral spectrum of electricity generation possibilities ranging from nuclear power, fossil fuels to RE (Keay 2016). The high degree of liberalization and ongoing energy legislations prevent a dominant market player. Instead, electricity generation is fragmented (market shares in 2016: EDF 24%, RWE 16%, Centrica 8%, Drax 7%, SSE 7%, E.ON 6%, Others 32%) and so is the retail market (market shares in 2016: British Gas 23%, SSE 15%, E.ON 14%, EDF 12%, Scottish Power 11%, RWE 10%, Others: 15%) (OFGEM 2017).

The German electricity market is the archetype of an environmental shift as its environmental dynamic began to evolve gradually with the first Renewable Energy Act in 2000 and two adjustments in 2004 and 2009 towards a higher share of RE through feed-in tariffs by 2011, with only minor governmental intervention (Renn, Marshall 2016; Szulecki et al. 2016). However, the environment changed dramatically in March 2011 due the prompt nuclear phase out by 2022 in reaction to the Fukushima accident. The amplitude of this punctuated change was very high as 22%

of gross electricity generation in 2010 was produced in nuclear power plants, 8 from 19 of which were shut down immediately. The decision to do was made within a short timeframe of only a few weeks (Renn, Marshall 2016). This could not have been predicted as the German government had voted for a lifetime extension of nuclear power plants in autumn 2010. After this dramatic environmental change, further legislation is occurring gradually and predictably. The aim is to guarantee reliable and competitive energy and to promote the diffusion and cost-efficiency of RE. Thus, the Renewable Energy Act of 2012 includes a market premium for RE and concrete achievements of 35% RE on total electricity consumption by 2020, >50% by 2030, and >80% by 2050. Further legislation includes fixed development-trajectories for RE (2014), roll-out of smart meters and grid (2016), and the implementation of tender-based auctions for RE (2017) (Federal Ministry for Economic Affairs and Energy 2017). Although the four big German energy incumbents (E.ON, RWE, Vattenfall, and EnBW) still represented 76% of electricity generation in 2015[5], the implications for competition were substantial. The four incumbents had to face a decrease in the retail segment from 43% in 2009 to 32% in 2015[5], and had to run extensive cost-cutting programs and organizational re-structuring. Table 11 summarizes the different market characteristics.

[5] Source: EU Commission, DG ENER, Unit A4, Energy Statistics; Energy datasheets: EU28 countries (update: 14. Feb 18)

France	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Total gross Electricity Generation, TWh	535.9	569.3	565.0	564.5	573.8	564.2	570.3	556.2
Gross Electricity Generation by fuel, %								
Solid Fuels	4.0	4.1	2.7	3.4	3.8	1.7	1.7	1.5
Gases	4.3	4.7	5.6	4.5	3.6	2.8	4.2	6.6
Nuclear	76.5	75.3	78.3	75.4	73.8	77.4	76.7	72.5
Renewables	13.9	14.6	12.3	15.6	17.8	17.3	16.5	18.4
Hydro	11.6	11.9	8.8	11.3	13.2	12.2	10.4	11.7
Wind	1.5	1.7	2.1	2.6	2.8	3.1	3.7	3.8
Solar	0.0	0.1	0.4	0.7	0.8	1.0	1.3	1.5
Other RE	0.9	0.9	1.0	1.0	0.9	1.0	1.1	1.4
Other	1.3	1.4	1.0	1.1	0.9	0.9	0.9	1.0
Energy dependency, %	50.8	48.9	48.6	48.1	47.9	45.9	45.7	47.1
No of main producers (>5% market share), No.	1	1	1	1	2	2	2	-
Cumulative market share of main producers, %	87.3	86.5	86.0	86.0	89.9	93.5	92.4	-
No of main retailers (>5% market share), No.	1	1	1	1	2	2	2	-
Cumulative market share of main retailers, %	85.5	85.0	79.0	79.0	85.6	87.2	86.7	-

UK	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Total gross Electricity Generation, TWh	376.7	382.1	368.0	363.9	358.3	338.1	339.4	
Gross Electricity Generation by fuel, %								
Solid Fuels	27.4	28.2	29.5	39.2	36.4	29.6	22.4	9.0
Gases	44.6	46.3	40.1	27.9	27.1	30.3	29.8	42.5
Nuclear	18.3	16.3	18.7	19.3	19.7	18.9	20.8	21.1
Renewables	7.7	7.7	10.4	12.2	15.7	19.9	25.4	25.4
Hydro	2.4	1.8	2.3	2.3	2.1	2.6	2.7	2.5
Wind	2.5	2.7	4.3	5.5	7.9	9.5	11.9	11.0
Solar	0.0	0.0	0.1	0.4	0.6	1.2	2.2	3.1
Other RE	2.8	3.2	3.6	4.1	5.1	6.7	8.6	8.9
Other	2.1	1.6	1.3	1.4	1.1	1.3	1.6	2.0
Energy dependency, %	26.4	28.2	36	42.2	46.3	45.5	37.4	
No of main producers (>5% market share), No.	8	8	7	7	7	7	6	-
Cumulative market share of main producers, %	80.0	77.3	75.3	81.0	80.7	78.9	74.6	-
No of main retailers (>5% market share), No.	6	6	6	6	6	6	6	-
Cumulative market share of main retailers, %	91.7	91.5	87.6	85.8	83.1	80.8	77.8	-

Germany	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Total gross Electricity Generation, TWh	595.6	633.0	613.1	629.8	638.7	627.8	646.9	649.1
Gross Electricity Generation by fuel, %								
Solid Fuels	42.6	41.5	42.8	44.0	45.1	43.7	42.1	40.3
Gases	14.9	15.9	15.8	13.9	12.5	11.6	11.5	14.4
Nuclear	22.7	22.2	17.6	15.8	15.2	15.5	14.2	13.0
Renewables	16.9	17.6	21.1	23.7	24.8	26.8	29.9	29.9
Hydro	4.1	4.3	3.8	4.4	4.5	4.1	3.8	4.0
Wind	6.5	6.0	8.0	8.0	8.1	9.1	12.2	12.1
Solar	1.1	1.9	3.2	4.2	4.9	5.7	6.0	5.9
Other RE	5.1	5.4	6.1	7.1	7.3	7.9	7.8	7.9
Other	3.0	2.8	2.6	2.6	2.4	2.4	2.3	2.3
Energy dependency, %	61.3	60.3	61.9	61.5	62.7	61.8	61.9	63.5
No of main producers (>5% market share), No.	4	4	4	4	4	4	4	-
Cumulative market share of main producers, %	70.0	70.4	58.9	56.2	74.0	73.0	76.0	-
No of main retailers (>5% market share), No.	3	3	4	4	4	4	4	-
Cumulative market share of main retailers, %	43.4	37.3	42.0	45.5	37.0	36.0	32.0	-

Source: EU Commission, DG ENER, Unit A4, Energy Statistics; Energy datasheets: EU28 countries (update: 14. Feb 18)

Table 11: Market Characteristics of the French, UK and German Electricity Market, 2009-2016

After identifying suitable electricity markets, I chose the sample firms EDF (France), SSE (UK), and E.ON (Germany) based on the following criteria to ensure that different BM changes are driven by different national environmental dynamics rather than firm-specific characteristics. First, all three firms depend to a high degree on their home market. Second, they meet the definition of an incumbent firm as they are “profit-seeking actors that are ‘established’ and ‘positioned’ in the markets [… and] have vested interests, historically accumulated capabilities, established supply chain linkages and institutionalized ways of operating” (Steen, Weaver 2017). Third, they are vertical-integrated energy utilities and cover (partly through subsidies due to unbundling and liberalization policies) major parts of the electricity value chain. Table 12 provides an overview of the key corporate data.

	2009	2010	2011	2012	2013	2014	2015	2016
EDF								
Revenue, in M €	68,362	65,178	60,791	74,789	78,384	66,754	73,836	67,807
Net Profit Margin, %	5.89%	1.57%	4.61%	4.56%	4.65%	5.08%	1.58%	4.00%
No. of employees	169,139	158,842	151,804	159,740	158,467	158,161	159,112	154,845
SSE								
Revenue, in M €	25,976	24,508	32,654	39,465	32,383	38,370	42,310	36,898
Net Profit Margin, %	0.44%	5.73%	5.31%	0.62%	1.50%	1.06%	1.72%	1.60%
No. of employees	18,795	20,177	20,249	19,49	19,795	19,894	19,965	21,118
E.ON								
Revenue, in M €	81,817	92,863	112,954	132,093	122,450	111,556	116,218	38,173
Net Profit Margin, %	11,79%	6,34%	1,33%	2,79%	2,24%	1,54%	0,42%	-8,92%
No. of employees	88,227	85,105	78,889	72,08	62,239	58,503	56,490	43,138

Source: Annual reports, Hoover`s corporate database (update: 4. Jan 18)

Table 12: Key Corporate Data on Electricity Incumbents EDF, SSE and E.ON, 2009 – 2016

3.4 Results

3.4.1 Case 1 - EDF in France

EDF emerged from the nationalization of hundreds of regional, privately-held energy firms in 1946. Nowadays, the French government still holds 85.6% of its shares and is obliged by law to hold at least 70%. EDF became the largest provider of nuclear energy worldwide and a global energy utility operating in 9 European countries, USA, China, Laos, and Vietnam. EDF has a dominant market position in France, with a market share of 87.3% in the residential customer segment and 65.0% in the business and local authorities segment at the end of June 2017. It operates the deregulated activities electricity generation and supply and covers the regulated activities through its legally unbundled subsidiaries RTE (transmission) and Enedis (distribution). Turning to EDF´s BM changes for its French electricity business, the value proposition is to provide low-carbon electricity in a safe, reliable, affordable and efficient way. This value proposition remains rather stable throughout the observation period as EDF’s current program “CAP 2030” has a clear focus on its low-carbon and reliable nuclear and hydro generation fleet, but also includes a tendency towards a higher level of solar and wind energy and a broader energy service offering. For residential customers, this broader value proposition includes tips for saving energy, a quicker handling of complaints, energy storage solutions, and e-mobility. For local authorities and industrial players, EDF offers local RE solutions (2010), real-time energy consumption data, energy optimization services (2012), e-mobility solutions with charging terminals and car-sharing (2013), and internet-based remote services and diagnostic tools (2014). The acquisition of Dalkia, a leading provider of energy services, in 2014 confirms this trend. Interestingly, these new services are primarily first tested and implemented abroad (e.g., in the UK) and, as in the case of distributed solar solutions, remain relatively small with a total of 210 employees and € 55 million revenues in France in late 2016. The natural and gradual evolvement also refers to the BM element infrastructure management as the fuel shares of EDF´s electricity capacity as an indicator for change maintains constant. Since the 1950s, EDF has had a high share of hydro power (70%). This was substituted by nuclear power and respective governmental investments in nuclear energy after the oil crisis in 1970s . Between 2009 and 2016, marginal increases in nuclear power (64.0% to 66.3%), hydro power (20.7% to 21.8%), and other RE (<0.5% to 1.1%) compensated for the decline in fossil-fired power (15.3% to 10.9%). Consequently, the sum of 58 nuclear reactors and over 430 hydropower plants remains stable, while the number of fossil-fired plants has decreased from 35 to 27. EDF’s commitment to nuclear power following the Fukushima accident in 2011 is seen in the intense safety upgrades and in design specifications for the nuclear fleet to withstand earthquakes and floods at an estimated cost of € 10bn (since 2011), extension of the operational lifetime beyond 40 years via upgrades of € 51bn until 2025 through the “Grand Carénage program” (2015), the acquisition of AREVA´s nuclear business with a value of € 2.47bn (2016), R&D

activities involving new European Pressurized Reactor models and small modular reactors (ongoing). A further expansion of the nuclear fleet in France has, however, been restricted by the Law on Energy Transition of August 2015 that limits the installed nuclear capacity in France to 63.2 GW. The planned grid connection of the new nuclear power plant Flamanville 3 EPR in 2019 thus requires the shutdown of an equivalent nuclear capacity elsewhere in France. With respect to RE, EDF fully acquired its renewable subsidiary EDF Énergies Nouvelles in 2011. EDF Énergies Nouvelles consequently increased its net installed capacity to 7,451 MW at the end of 2016, but its growth abroad was primarily due to more favorable support mechanisms for RE. Almost half of its net installed capacity is located in North America and a quarter in Europe (excluding France). EDF Énergies Nouvelles increased its net installed capacity for France from 494.5 MW in 2011 to 1,025.0 MW in 2016, which equals 1.1% of EDF's installed capacity in the domestic market. This confirms the marginal adjustments within infrastructure management for the French market. A marginally higher degree of changes is evident within the BM element customer interface. EDF's customer segments are consistent throughout the observation period and include corporate and business customers (50% of electricity sold), residential customers (40%), and local authorities (10%). Its customer relationship, however, shifted from a "smooth and straightforward" (EDF 2009, p.11) to a closer and more digital relationship, the channels of which differ by customer segment. For the residential mass-market, EDF uses a broad spectrum of channels including call centers, sales representatives in the field, boutique-styled agencies as well as a growing number of digital channels. This evolution started in 2009 with the first "Ma Maison Bleu Ciel" websites and newsletters that provide advice on energy-saving, contact with installers, and other consulting services. Over the years, digital channels and offerings expanded to the new mobile application "Étiquette énergie" to define the energy consumption of electric devices (2010), online invoicing, self-assessment tool and automated voice portal (2011), electronic billing, SMS payment and enhanced interactive voice server for complaint handling (2012), photo meter reading and smart meters (2013), the inclusion of almost 4,000 home solutions partners and more personalized digital solutions called “EDF & Moi” and “e.quilibre” for personal energy tracking and savings advice (2015), co-innovation platform “Pulse&You” (2016) as well as solar self-consumption opportunities “Mon Soleil&Moi” (2017). For business customers and local authorities, single advisors in addition to digital channels guarantee a customer relationship built on trust. For the BM element financials, EDF spends a constant share of 60% of its net investments on deregulated activities (generation, sales, optimization and trading) and 40% on regulated activities (distribution, transmission). The regulated activities, however, have a greater influence on the operating profit as its share steadily increased from 34.1% in 2011 to 50.5% in 2017. Qualitative statements on financials highlight a two-fold investment strategy with equal spending on RE as well as on optimization and safety upgrades at nuclear and hydro plants.

3.4.2 Case 2 - SSE in UK

In 1998, Scottish Hydro-Electric merged with Southern Electric to become Scottish and Southern Energy, which was renamed SSE in 2011. SSE is the second largest vertical-integrated electricity provider in the UK, generating 98% of its revenues in the UK domestic market. Its value proposition remained constant between 2009 and 2017 and aims to provide SSE’s customers with electricity in a reliable and sustainable way through a diversified portfolio of conventional and RE generation together with energy services. Regarding infrastructure management, SSE follows its guideline of disciplined investments, balanced business, efficient operations, and the avoidance of over-exposure to a certain type of electricity generation. For the period 2009–2011, gas and oil accounted for 40%, RE for 21%, and coal for 39%. In order to align with the decarbonization targets of the UK government, between 2011–2014, SSE substituted the decline of coal power (-12.9 percentage points (ppt)) almost equally with increases in gas & oil (+6.1ppt) and RE (+6.8ppt). The resulting portfolio share for the years 20142016 was thus gas and oil 46%, RE 28%, and coal 26%. Another example of this alignment behavior was the sale in late 2011 of its 25% stake in the nuclear joint venture NuGeneration (together with GDF Suez and Iberdrola) shortly after its foundation in 2010 and as a reaction to the unclear political situation following the Fukushima accident. Further investments and disposals across various types of generation sources primarily through joint ventures strenghten this BM adaptation behavior (e.g., 2009: two 50:50 joint ventures with DONG Energy (1,000MW; offshore wind) and Viking Energy (540MW; onshore wind), 2012: SSE (600 MW; hydro), 2013: 50:50 joint venture with RWE npower (500MW; offshore wind), 2016: sale of 350MW wind farm, 2017: investment in Dogger Bank, offshore wind). Regarding the BM element customer interface, SSE seeks to build a trustful and direct relationship with its customers and to create a local, reliable, digital-driven, and service-orientated brand image. Underlying initiatives include the opening of a flagship office (2011) for Engineering Excellence for Renewable Energy, a first-time UK-wide binding Customer Service Guarantee including discounts for customers (2013), massive investments in the roll out of smart meters from 300 to 500,000 units between 2013 and 2017. Regarding customer channels, digitalization gained momentum in 2009 and mail overtook letters as the second most important customer interaction mode. The share of online customer communication channels (e.g., mail, online service platform, mobile billing, and meter reading) grew from 33% in 2011 to 50% in 2013 and 70% in 2016. Key milestones include the launch of social media activities on platforms such as Facebook and Twitter (2012), an online service platform for small and medium businesses

(2014), real-time information on energy consumption, grid maintenance works, and weather forecasts (2015), and enhanced mobile applications (2016). Most fundamentally, SSE changed the BM element financials as it shifted investments from the non-regulated business segment wholesale (-30.4ppt, 2009-2017) to the more stable, regulated network business (+21.4ppt) and left expenditures for the segments “retail” and “others” nearly constant. This shift resulted in an increasing share of the network segment to the operating profit (+12.3ppt) and a decrease in the wholesale business (-26.7ppt). The substantial increase in the retail segment (+14.4ppt) was achieved in the face of decreasing customer numbers (5.1 to 4.1 Mio), increasing competition, and the highest switching levels in UK market history. It is driven by higher electricity prices and the sale of additional energy services, which reflects the broader value proposition.

3.4.3 Case 3 - E.ON in Germany

E.ON was born of the merger of the two German industrial companies VEBA and VIAG in 2000 and, alongside RWE, Vattenfall, and EnBW, is one of the four dominant energy utilities in Germany. Since 2011, E.ON has been organized into 5 global and 12 regional units with subordinate support functions such as IT, procurement, and controlling. Following the Fukushima accident in 2011 and the resulting nuclear phase-out in Germany, E.ON fundamentally changed its “broad-based business model” (E.ON 2014, p.4) to make it leaner, more agile and customer-centric. This process led to the spin-off Uniper (announced in November 2014, executed in 2016) and major changes within each BM element. Starting with the value proposition, E.ON offered its customers a relatively comprehensive value proposition at the beginning of the observation period. Besides its core business of large-scale energy generation and distribution, E.ON addressed decentralized energy generation, e-mobility, smart home solutions, and storage opportunities. Following the establishment of the spin-off Uniper, which operates the conventional power sources (coal, gas, oil, hydro) and energy trading, E.ON's new value proposition began to focus on energy provision mainly through wind power, smart and digital customer solutions, and the network business. The BM element infrastructure management also underwent profound changes after the Fukushima accident in 2011. E.ON's share of nuclear power dropped from 36.6% in 2010 to 26.0% in 2011 and remained rather stable until 2015 with 28.2%. Between 2009 and 2015, the share of coal power declined by 6.7ppt, while oil & gas increased by 12.0ppt, hydro by 2.8ppt, and wind by 2.3ppt, which is a massive expansion compared to its marginal share of 0.9% in 2009. The portfolio changed fundamentally in 2016 after the organizational split of E.ON and Uniper. Its total electric capacity shrank from 22,939 MW in 2009, 18,006 MW in 2014 to 4,600 MW in 2016, with nuclear accounting for 89.8% and wind for the remaining 10.2%. It is important to note, however, that E.ON describes its nuclear business as a non-core activity that is processed by its subsidiary PreussenElektra. The key activities of E.ON in 2009 were conventional and RE generation, energy trading, and infrastructure management. In 2016 and in line with its customer-centric orientation, E.ON identified energy networks, customer solutions, and RE as its core business. Energy networks refers to the reliable operation, maintenance, and expansion of the electricity network. Customer solutions compromises the promotion of digital products and services for individual customer needs, energy efficiency, and autonomy. The RE segment contains the development of onshore and offshore wind. E.ON`s leaner setup also affects its key partnerships. Besides partnering with major players such as Deutsche Telekom for smart home applications, Viessman for heating-systems as well as Volkswagen, BMW, Siemens and car leasing firm Sixt for e-mobility, E.ON has intensified its partnerships with German start-ups in recent years. The objective hereby is to identify early-on innovative technologies and BMs for a decentralized, digital, and RE environment, e.g., Thermondo for customer energy saving advice (2014) and prosumergy for green electricity (2015). To support this more agile innovation approach, E.ON strengthened its partnerships with universities and research institutes (particularly with the RWTH Aachen) and launched a program for strategic co-investments in 2012 as well as a technology and innovation incubator in 2013, which expanded into the E.ON "agile accelerator" in 2014. E.ON thus reduced its development time, limited its risk exposure and covers early on emerging technology fields such as smart home solutions for solar power surplus (2012), virtual power plants, power-to-gas storage solutions (2013), use of drones for power line inspections and predictive maintenance of plants and turbines; large scale modular battery storage systems (2014) or machine learning techniques for grid optimization (2015). Regarding changes in the BM element customer interface, E.ON followed a holistic customer approach to address the full spectrum of customer segments at the beginning of the observation period. Up until 2015, the share of residential customer and small businesses ranged between 16–24%, industry and commercials accounted for 18–26%, and sales partners enjoyed a stable share of 60%. This distribution of customer segments changed essentially in 2016 due to the spin-off Uniper. The relevance of residential customers and small businesses increased to 64%, industry and commercials accounted for 33%, and sales partners declined to a marginal share of 1%. The absolute sales volume declined from over 140kWh in 2009 to 78kWh in 2014 and 28kWh in 2016. Regarding customer relationship, E.ON sees its residential and industrial customers as prosumers as it provides them transparency in energy consumption but also advises them on local, small-scale energy generation. E.ON developed a closer, customer-centric, and more digital interaction throughout the observation period, examples of which include an early engagement in smart home applications together with Deutsche Telekom and Telefunken (2011), the founding of E.ON "Connecting Energies," which is dedicated to developing digital and decentralized all-in-one energy solutions for industrial, commercial, and public customers (2012), local rebranding and reorganization of retail business as well as the implementation of a customer loyalty program (2013), the establishment of a Digital Transformation Unit (2014), a Chief Digital Officer (2015) and constant improvements to leading smartphone applications (2016). The strengthened customer focus is also reflected in E.ON`s mission statement, which changed from “cleaner & better energy” (2010) to “Empowering customers. Shaping markets” (2014) and the customer inclusive “Let`s create a better tomorrow” (2016). E.ON thus uses the full spectrum of customer communication channels like telephone, mail, internet, mobile applications, and personal advisors and was already investing in social media activities like Youtube in 2009. Over the years, communication and service channels have become more digital, e.g., online billing and meter reading; smart home applications for lightning, heating, and security; or the E.ON Solar Cloud for virtually storing and managing customer generated solar energy (2016). Changes within the BM element financials are difficult to identify in the German business unit as E.ON reports the majority of key financials on a group level. However the existing data for the German business indicate a substantial shift for sales contribution from the non-regulated business (2010: 71.1%, 2016: 37.1%) to the network business (2010: 28.9%; 2016: 62.9%). On the cost side, E.ON was faced with non-recurring negative financial effects of 1.5bn due to the nuclear phase-out in Germany and thus launched the group-wide cost-reduction program “E.ON 2.0” of 2bn € in 2011 and the further cost-reduction program “Phoenix” of 0.4bn € in 2016. Investments concentrated on the network business (1bn € in 2015) and the settlement of nuclear operations (10bn € agreement on responsibility for nuclear waste with German government in 2016).

3.5 Discussion and Cross-case Analysis

The cross-case findings include important aspects for (a) discussing Saebi`s theory on the contingency framework of BM changes and (b) overarching BM trends observable at the sample utilities. Regarding (a) theory development, the BM changes in the three cases tend to confirm the theoretical assumptions of Saebi`s contingency framework and are summarized in Table 13.

BM element	EDF	SSE	E.ON
Value Proposition	Incremental	Incremental	Radical
Customer interface	Incremental	Incremental	Radical
Infrastructure Management	No change	Incremental	Radical
Financials	No change	Radical	Radical

Table 13: Summary of Main BM Changes of Electricity Incumbents EDF, SSE and E.ON, 2009 – 2017 Aligned with Saebi's (2015) Contingency Framework

I find basic support that the BM changes at EDF correspond to Saebi's (2015) proposed archetype of a *BM evolution* under the environmental dynamic *regular change* as it leaves infrastructure management constant and only adjusts the remaining BM elements to an incremental degree. EDF stays to its value proposition of low-carbon electricity generation mainly based on nuclear and hydro power. It also retains a constant customer segmentation within the BM element customer interface and does not change its investment spending of the BM element financials. The incremental changes are driven by a marginal broader value proposition as well as a closer customer relationship, with more customer-orientated and digital channels. In summary, its focus is however to gradually adjust the current BM within a natural trajectory and apply a “defensive strategy to protect its market share” (EDF 2015, p.101).

BM changes at SSE can be classified under *BM adaptation* as predicted by theory under the constraints of *environmental competitiveness*. SSE broadened its value proposition incrementally and personalized the customer interface due to digitalization and increased customer demand for energy services, which is in line with EDF’s BM changes. However, SSE’s scope of BM changes is wider as it also changed the BM elements infrastructure management and financials and marginally more radically within each one compared to EDF. The balanced generation portfolio with an increase in RE and the sale of nuclear activities, an increasing level of digital energy services and channels as well as a focus on the regulated network business are all targeted at aligning the BM with the *environmental competitiveness*. This corresponds to the proposed planned outcome of *BM adaptation*.

The case-study provides a list of examples that E.ON, confronted with an *environmental shift* after the prompt nuclear phase out in Germany, acted according to the archetype *BM innovation* as it radically changed all BM elements and its organizational structure. The Uniper spin-off enabled E.ON to define new market conditions through an agile organization as well as a customer-centric, digital, and green BM. This BM clearly differs from previous energy utility BMs based on conventional electricity generation and its supply as a commodity. It is thus new to the industry and its BM change occurred infrequently within the observation period.

For (b) overall BM trends in the energy sector, I find four potential insights, which apply to a certain degree and scope to all three sample utilities. First, all three sample firms broadened their value proposition from a pure commodity provider of electricity towards a customer-orientated service provider. This development includes a higher service-level for their core business electricity, but also implies a larger and more digitalized product portfolio including smart home applications and e-mobility-solutions. Second, the customer interface is more customer-centric, and thus changes from a passive to an active consumer view. A more active customer role starts with a higher level of service-orientation, energy saving advice, and the inclusion of customer feedback. It further includes online billing and mobile meter reading and ends with a prosumer component for small-scale wind, solar, and biomass power plants, particularly at E.ON. The customer relationships have thus become more direct and closer, which was achieved through an intensified usage of digital customer communication channels such as smartphone apps, online service platforms, and social media. Third, the share of RE within the infrastructure management has become more important in order to comply with ambitious political climate targets and customer demands for clean energy. This BM element, however, reveals the largest differences as EDF upgrades and maintains its nuclear power plants, SSE evenly adjusts its portfolio towards less coal, and E.ON fundamentally reorganizes its key activities and organization through the Uniper spin-off (see Figures 3 to 5). Fourth, increased competition, required investments in greener and more digital energy solutions, post-Fukushima costs on the nuclear fleets put pressure on utilities' *financials*. All of the sample firms run cost-cutting programs in order to be more efficient and re-evaluate their investments: EDF invests intensively in safety upgrades for its nuclear power plants, SSE balances its generation portfolio and invests in a higher customer attractiveness, and E.ON invests heavily in RE, network business, and customer solutions. If possible, they shift their revenue streams from the unregulated retail segment to the regulated and stable wholesale and transmission business. In addition, revenues from energy services and customer solutions become more important.

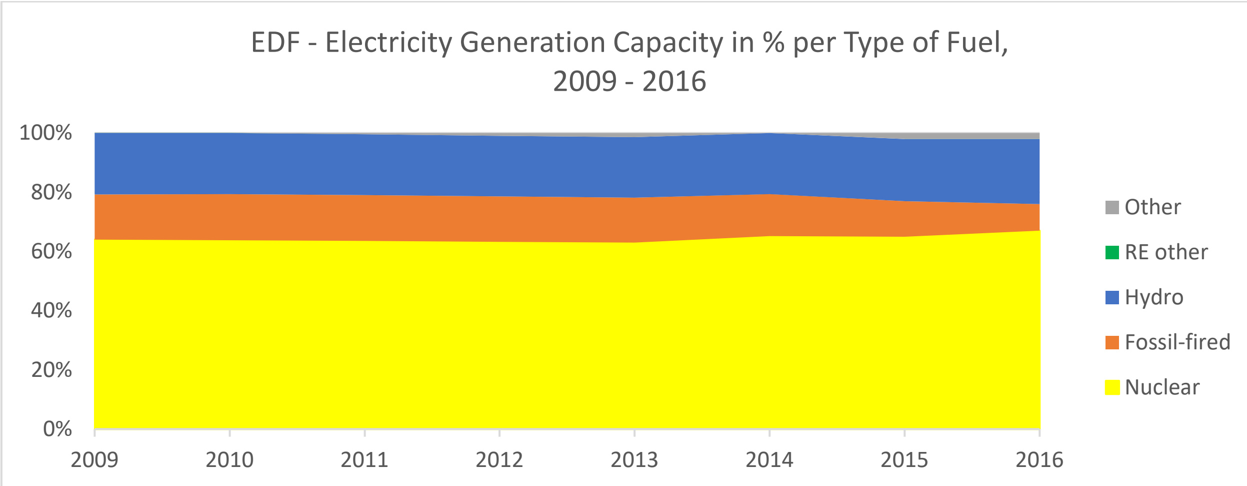

Figure 3: Share of Electricity Generation Capacity for EDF in % per Type of Fuel, 2009 - 2016 as Indicator of the BM Element *Infrastructure Management*

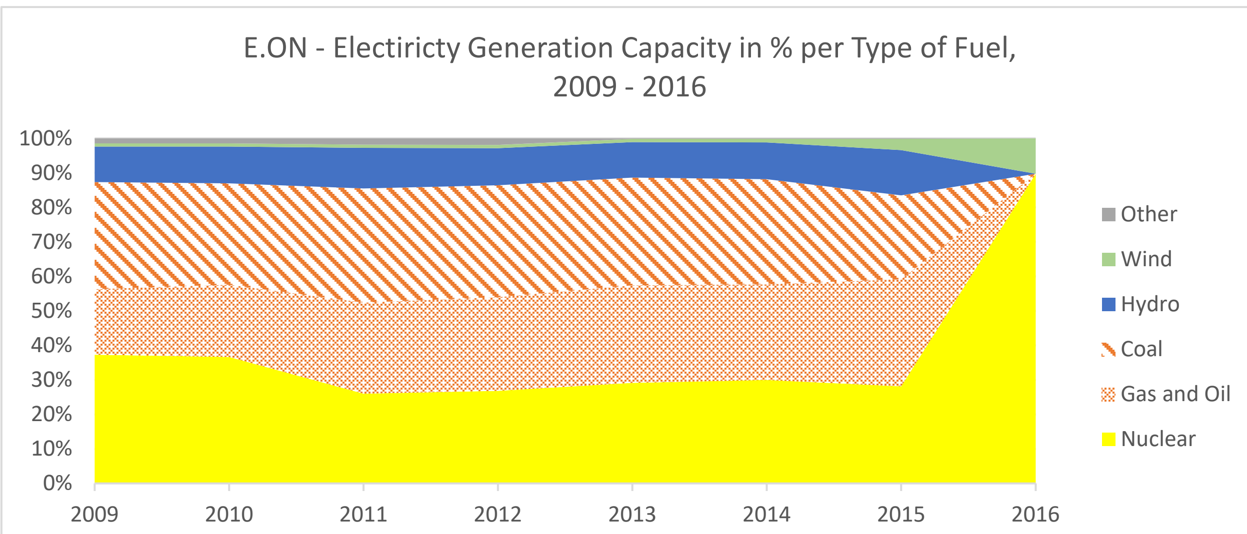

Figure 4: Share of Electricity Generation Capacity for E.ON in % per Type of Fuel, 2009 - 2016 as Indicator of the BM Element *Infrastructure Management*

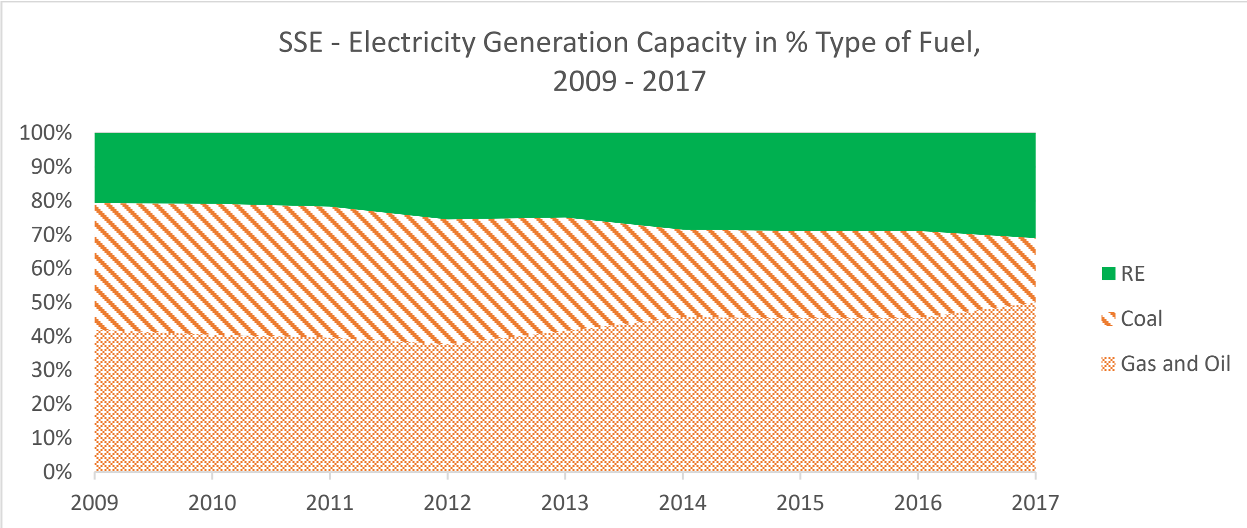

Figure 5: Share of Electricity Generation Capacity for SSE in % per Type of Fuel, 2009 - 2017 as Indicator of the BM Element *Infrastructure Management*

3.6 Conclusion

3.6.1 Summary of Main Findings and Theoretical Implications

The primary purpose of this paper is to discuss the contingency framework of BM changes put forward by Saebi (2015) for energy incumbent firms in different legal environmental dynamics. The applied research question is thus whether different environmental dynamics in terms of frequency, amplitude, predictability and velocity cause distinguish BM changes measured by its planned outcome, scope of change, degree of radicalness, frequency of change and degree of novelty. The insights of the multiple case-study (Yin 2009) provide certain evidence to confirm Saebi`s (2015) theory: EDF in the stable environment regular change applied a BM evolution. It evolved its BM naturally and gradually, with only an incremental radicalness, as it keeps its customer segmentation and infrastructure management of nuclear and hydro power constant. SSE, under environmental competitiveness, follows a BM adaptation. It aligns its BM with the environment, as it adjusts its generation portfolio slightly, broadens its value proposition through digital services, and implements a more customer-centric customer interface. E.ON executes the most radical and widespread BM changes, which led to the organizational split from Uniper and enabled E.ON to define new market conditions based on RE and digital customer solutions. This is in line with the BM innovation caused by environmental shift predicted in Saebi`s (2015) theory. The second observation of the case-study is the identification of trends in BM changes, which occur independent of the legal environmental dynamics. These trends include a broader value proposition, a more digital and customer-orientated customer interface, an infrastructure management with a higher share of RE, and a shift within financials towards regulated businesses. I see three possible root causes for these trends. First, increasing customer demands for more convenient, self-regulating, and greener energy solutions. Second, the technological development of RE, digital customer channels, and smart grid applications, which allow their cost-competitive implementation. Third, increased competition in de-regulated businesses through smaller and agile new entrants, which forces incumbent firms to foster innovation and concentrate on regulated businesses. This finding has a theoretical implication for Saebi`s (2015) contingency framework as the term environmental dynamics should not only focus on energy laws and regulations like in this paper, but also account for changes in customer needs, technology, and competition. In addition, I further develop Saebi`s contingency framework in two dimensions by combining it with the BM CANVAS. First, it allows a more granular and structured discussion as its level of analysis is not the entire BM but the explicit BM elements value proposition, customer interface, infrastructure management, and financials. Second, my analysis consists of various quantitative and qualitative indicators for BM changes, which facilitate the operationalization of theory.

3.6.2 Policy and Managerial Implications

The findings of the above case-study base on three sample firms, therefore they have to be interpreted cautiously and are rather potential options than proven recommendations. For policy makers, two possible implications might result. First, laws and regulations provide policy makers with an effective measure for influencing incumbent`s BMs and pointing them towards socially and environmentally-desirable behavior. Second, they indicate that a high share of governmental interference and rigid political environments do not stimulate firm innovativeness, as in the case of EDF. Fundamental and unpredictable political changes as the other extreme, however, lead to abrupt BM changes and organizational restructuring, with high financial risks for the affected firms, (as with the sample firm E.ON and its peer RWE in Germany). Concluding possible implications for policy makers are to align new laws and regulations with the domestic industry, communicate them early on, and implement regular, non-binding discussion platforms.

Based on the observations of the three sample firms, I would propose four beneficiary options for managers. First, the results give a general guidance on the necessity, scope, radicalness, and frequency of BM changes in response to different legal environmental dynamics. The outlined differences between EDF, SSE and E.ON can serve as potential role models for companies across all sectors, especially for multinational ones, as they face the complexities of adjusting their BMs to different environmental dynamics simultaneously. Second, I find first indications that in the case of *environmental shifts*, fundamental BM changes might also occur in the energy sector. This is relevant, as energy utility mangers have underestimated in the past to develop corresponding capabilities proactively (Richter 2013; Gsodam et al. 2015). An option based on the observations of the case-study for managers and employees is to be open to BM changes. To do this, I suggest managers in the electricity sector to continue along the path towards more open and agile innovation initiatives, e.g., EDF with start-up financing (since 2012), E.ON with start-up cooperation, and all sample firms with cross-sectoral partnerships (e.g. automotive, telecommunication). Third, the results not only call for higher innovativeness, but also possibly indicate an increased service level and a customer-centric perspective. The value proposition of energy incumbents tends to be no longer the provision of electricity as a commodity, but demands digital, convenient, and integral customer solutions. Investments in new digital services should therefore cover the core electricity business (e.g., online billing, meter reading, complaint management, small-scale electricity generation), but also include security, heating, smart home applications, and e-mobility. Fourth, a potential option for policy makers is a transparent and early on communication of upcoming laws to allow managers to prepare BM changes accordingly.

3.6.3 Limitations and Suggestions for Future Research

I leave room for further BM research with this paper as its selective and conceptual case-study approach is not without its limitations. Although I conduct intense research on comparable and reliable data for BM changes, further information (above all, for partnerships, suppliers, and sales channels) is required. In addition, the three sample firms do not use the same reporting standards nor is the breakdown of group-level data to country-level simple, which impedes comparability. Finally, the case-study design is subject to selection biases, which limits the generalization of the results. Thus, future research should re-confirm the findings using quantitative research methods on a broader firm sample. This allows researchers to control for further incumbent characteristics (e.g., size, ownership, value chain coverage, international presence) and to include a broad set of variables for changing environmental dynamics (e.g., by the number of new entrants, public opinion via poll data, diffusion rate of certain technologies). I recommend a start-up perspective as this paper focuses on energy incumbents. There is substantial research potential for either the analysis of innovation cooperation or collaborative BMs. Suitable start-ups include, e.g., virtual power plant operators, weather forecast companies, small-scale RE providers, or e-mobility-manufacturers. Finally, organizational studies should use the findings to derive implications of BM changes for organizational re-structuring, recruitment, and personal development processes. Relevance for this research lies in the observed request for service-orientated employees rather than efficiency-driven technological experts as in the past.

4. Paper 3: Drivers of the Global Knowledge Spillovers in the Energy Sector and the Determinants of a Firm`s Potential Absorptive Capacity

4.1 Introduction

As firms today face faster innovation cycles, global competition and inter-organizational R&D collaboration, increased customer demands, and blurred industry boundaries, they have come to rely on external knowledge, i.e., knowledge from outside their own organizational, geographic, and technological scope (Araújo Burcharth et al., 2015; Ferreras-Méndez et al., 2016). External knowledge is highly relevant in industries such as the renewable energy sector and, in particular, the photovoltaic (PV) sector. These are characterized by international value chains (Zhang and Gallagher, 2016), spatial lifecycle dynamics (Binz et al., 2017), technological proximity to the chemical, electronics, and electrical sectors (Nemet, 2012), small diffusion rates (Negro et al., 2012), capital intensiveness, knowledge depreciation and substantial cost reduction potential through learning (Gallagher et al. 2012). However, the growing literature on energy technology innovation systems (ETIS) deems knowledge acquisition and learning to be one of its key research gaps (Gallagher et al. 2012). This is surprising since a profound understanding of international and intersectoral knowledge flows is not only a prerequisite for energy firms to compete, but also for policy makers to implement effective instruments to reach their climate protection targets.

Cohen and Levinthal (1989, 1990) introduce the concept of a firm`s absorptive capacity (ACAP) and lay the theoretical foundation for a better understanding of how firms identify and acquire external knowledge flows, incorporate them in their internal R&D organization, and apply them to commercial ends. Alongside further theoretical contributions (from, e.g., Lane et al., 2006; Lichtenthaler, 2016; Zahra and George, 2002), scholars highlight the practical relevance of ACAP for firms, regions, and countries (Castellacci and Natera, 2013; Lewandowska, 2015; Miguélez and Moreno, 2015). While the growing number of publications reflects the scientific interest in the relationship between knowledge flows and ACAP (Volberda et al., 2010), the empirical examination of both topics remains challenging due to the often tacit nature of knowledge flows (Gallagher et al. 2012), their multidimensional characteristics (Battke et al., 2016; Jensen et al., 2007), their diverse channels such as imitation, trade, and labor mobility (Grübler et al., 2012) as well as the various definitions of and measurement methods for ACAP (Camisón and Forés, 2010; Flatten et al., 2011; Jiménez-Barrionuevo et al., 2011; Lewandowska, 2015). I therefore limit my analysis to codified knowledge in the form of patent and citation data and focus on a firm`s potential absorptive capacity (PACAP), i.e., the first part of ACAP that includes the acquisition and assimilation of external knowledge (Zahra and George, 2002). This tailored patent-based approach allows me to first visualize international and intersectoral knowledge flows and describe patenting patterns for a high number of German PV firms over a long period (1976–2015) in order to then derive the determinants of a firm`s PACAP. The paper answers two consecutive research questions: (1) What are the main characteristics of knowledge flows and patenting patterns affecting the German PV sector? (2) Which factors determine a PV firm`s PACAP?

In answer to the first question, a detailed examination of 1,782 patent applications, 8,573 cited patents, and 5,210 citing patents for 148 German PV firms from 1976–2015 shows growing patent activity since the mid-1990s along with a higher inclusion of female inventors, larger inventor teams, intensified industry-university R&D collaboration, and the constant presence of co-patenting initiatives (see Section 3.3). On average, inventors cite 4.81 patents per patent application, with a citation lag of 9.06 years, which serves as a first indicator of the scope and timespan of recognized external knowledge. Between 1976 and 2015, 58.19% of the cited patents come from foreign firms and 49.21% from outside the PV sector, which shows the dependency on international and intersectoral knowledge flows.

Based on these insights and in order to answer the second research question, I group the hypotheses on a firm`s PACAP into two sections to account for inventor diversity and inter-organizational R&D collaboration, and add a set of control variables for the surrounding ecosystem. Furthermore, I apply this second research question to general, international, and intersectoral knowledge flows to examine whether different types of knowledge flows require different PACAP determinants. For the first hypothesis on inventor diversity, my analysis shows that larger and gender diverse inventor teams absorb more knowledge along all three dimensions, cultural diversity has a significant positive effect on capturing international knowledge flows, but there is no significant effect for inventor teams with higher educated members to increase a firm`s PACAP. The results for my second hypothesis highlight the benefits of international and industry-university R&D collaborations for a firm`s PACAP, but also reveal negative effects for a higher number of co-patenting actors. My control variables on eco-systematic factors confirm a significant positive effect of academic R&D linkages measured by spatially proximate universities. In contrast, PACAP decreases with the number of spatially proximate PV firms. Network ties with governments have no significant effect.

This paper differs from previous studies in four aspects. Firstly, the approach combines the empirical assessment of knowledge flows with the theoretical concept of PACAP. Secondly, patent and citation analysis provides access to a broad but also granular dataset in an objective manner and thereby differs from content-related, survey-based studies (e.g., Araújo Burcharth et al., 2015; Camisón and Forés, 2010; Ferreras-Méndez et al., 2016). A third distinction is the holistic view of my methodology, which covers individual inventor-related, inter-organizational, and eco-systematic determinants, satisfying thereby the call for comprehensive research on ACAP and effective R&D collaboration (Volberda et al., 2010). Finally, the analysis not only evaluates knowledge flows in general, but an intense coding effort allows me to also analyze distinctive kinds of knowledge, namely international and intersectoral knowledge flows, as requested by Lewandowska (2015).

The paper proceeds as follows. Section 2 outlines the background literature on the concept of ACAP and derives hypotheses for inventor-related and inter-organizational factors to explain different levels of a firm`s PACAP. Section 3 describes the methodology of patent-citation analysis and the data sample. It also presents patent patterns and knowledge flows affecting the German PV sector. Section 4 provides the empirical application and main results. Section 5 concludes with theoretical and practical implications and suggests further research areas.

4.2 Theoretical Background

4.2.1 The Concept of ACAP

The concept of ACAP was originally linked to a nation`s economy and later adapted to firms (Lewandowska, 2015). The growing literature on a firm`s ACAP has led to a variety of definitions and conceptualizations. Cohen and Levinthal (1989) point to the dual role of a firm`s R&D activities in not only generating innovation but also developing a firm`s ACAP. They define ACAP as a "firm`s ability to identify, assimilate and exploit external knowledge from the environment" (Cohen and Levinthal 1989, p.569). In contrast to learning by doing, i.e., a firm`s development in an existing field, ACAP enables a firm to expand into new fields. On this basis, Cohen and Levinthal (1990) discuss individual and organizational ACAP and emphasize the role of prior related knowledge and diversity. They also place ACAP in a broader organizational context that includes, e.g., communication structures, cross-functional linkages to manufacturing and marketing, knowledge management, and R&D cooperation. They adjust the previous definition of ACAP to a firm`s capability to value and assimilate external information and apply it to commercial ends. An extension of this definition includes the capability to predict future technological developments more precisely (Cohen and Levinthal 1994).

Zahra and George (2002) highlight the dynamic capability nature of ACAP and its embeddedness within firm`s routines and processes. They outline four distinctive but complementary dimensions. *Acquisition* refers to a firm`s capacity to identify and acquire relevant external knowledge. *Assimilation* relates to routines and processes that enable a firm to analyze, process, interpret, and understand the acquired knowledge. *Transformation* is the development of internal routines to align and combine the existing knowledge with the external knowledge through its modification and new interpretation. *Exploitation* points to a firm´s organizational capacity to incorporate acquired, assimilated, and transformed knowledge into their operations and routines in order to enhance them and achieve commercial benefits. The first two dimensions (acquisition and assimilation) are clustered into potential absorptive capacity (PACAP) and the last two dimensions (transformation and exploitation) define realized absorptive capacity (RACAP).

Following a meta-analysis of 289 papers on ACAP, Lane et al. (2006) develope a new conceptualization linking ACAP to organizational learning. They define three sequential processes. *Exploratory learning* is the ability to recognize and understand potentially valuable external knowledge. *Transformative learning* assimilates valuable new knowledge and links exploratory learning with *exploitative learning*, which creates new knowledge and commercial output.

Based on the literature review on ACAP (in addition to the studies above and more recent examples such as Apriliyanti and Alon, 2017; Ferreras-Méndez et al., 2016; Lewandowska 2015; Volberda et al. 2010), I identify a list of similarities of a substantial nature. ACAP is a multi-dimensional, complementary, past-dependent dynamic capability enabling a firm to achieve competitive advantage and relies on an individual's cognitive capacity, organizational structures, and network ties. Different views within the scientific discussion refer not only to the number of dimensions but also its sequence (Todorova and Durisin 2007), an appropriate measurement of ACAP (Flatten et al., 2011; Jiménez-Barrionuevo et al., 2011), and the field of application, which emerged from an R&D focus towards a broader organizational setting (Gebauer et al., 2012). This paper follows the clear distinction between PACAP and RACAP in the tradition of Zahra and George (2002). I define PACAP as the identification, valuation, acquisition, interpretation, and understanding of external knowledge, which is a separate, preceding process of aligning, combining, and integrating the recognized valuable knowledge into the existing knowledge stock. Acknowledging the multifaceted work on RACAP and how it affects a firm`s R&D performance (Sjödin and Frishammar, 2015), I focus on the rather neglected antecedents of PACAP and tailor my hypotheses and methodology accordingly.

4.2.2 Inventor Diversity and a Firm`s PACAP

While previous studies (Cohen and Levinthal, 1990; Enkel et al., 2016; Volberda et al., 2010) emphasize the importance of employees' diversity and their individual ACAP for a firm´s ACAP, few empirical studies exist (Sjödin and Frishammar, 2015; ter Wal et al., 2011).

Empirical studies on diversity and group performance in general draw a heterogeneous picture ranging from increased creativity and innovation outcome to miscommunication, personal conflicts, and discrimination (Østergaard et al., 2011; Roberge and van Dick, 2010). I argue that a firm`s PACAP increases through a larger and more diverse inventor team with a required common cognitive base of shared knowledge, language, and routines. First, the ability to link external with existing knowledge depends on the memorized prior knowledge base of a firm`s employees (Cohen and Levinthal, 1990), which increases with their number and diversity. Second, access to relevant external knowledge depends on the size, heterogeneity, and quality of personal networks. A larger and more diverse inventor team has more network ties to productive knowledge than does a single inventor. Third, working in larger and diverse inventor teams prevents cognitive lock-ins (Crescenzi et al., 2016) and requires the capability to be willing to learn from others, interact more intensively, collaborate beyond an individual's horizon, and actively search for unfamiliar knowledge. Jansen et al. (2005) emphasize a positive relationship between PACAP and diversity (indicated by cross-functional interfaces and job rotation). Finally, a higher number of inventors indicate additional resources and the entrepreneurial freedom to establish dedicated and extensive search activities, which positively affects PACAP (Araújo Burcharth et al., 2015; Enkel and Heil, 2014; Sjödin and Frishammar, 2015). I conclude:

H1a: *A higher number of inventors increase a firm`s PACAP.*

Besides additional perceptual views and a heterogeneous knowledge base, cultural diversity has a positive effect on a firm`s PACAP as the dominant role of the English language among inventors and enhanced global communication structures cannot overcome all cultural and linguistic barriers to acquiring external knowledge and adapting it to domestic circumstances.

In addition, culturally diverse inventors have a higher awareness of upcoming technological and market knowledge in their home countries through personal interest or contacts. They are therefore better able to identify new external knowledge and value its linkages with the existing knowledge base, especially with respect to foreign knowledge.

H1b: *A more culturally diverse inventor team increases a firm`s PACAP.*

A recent study by Meng (2016) examines the collaboration and patent behavior of female academic scientists and contradicts the belief that women have smaller and less powerful networks and are reluctant to leverage them. Such arguments would result in a negative relationship between female R&D participation and PACAP. In addition, Meng points to the ability of women to build up external relationships with a higher level of trust. I rate trust as an important pre-condition for PACAP and knowledge exchange given the dominating tacit nature of knowledge and its strategic importance for firms. Beside trustful relations, reviews on gender diversity (e.g., Perryman et al., 2016; Quintana-García and Benavides-Velasco, 2016; Ruiz-Jiménez and del Mar Fuentes-Fuentes, 2016) emphasize women`s different perspectives and alternative problem-solving approaches as well as an extended search for new information. Finally, they argue that women enhance group involvement and the level of interaction within organizations, which affects PACAP positively (Cohen and Levinthal, 1990).

H1c: *A gender diverse inventor team increases a firm`s PACAP.*

I assume a positive relationship between employees' educational level and PACAP for various reasons. First, graduated R&D personnel have a broader and frequently trained knowledge base, which enables them to scan the external knowledge environment more efficiently and value its potential appropriately (Cohen and Levinthal, 1990), and reduce the information overload (ter

Wal et al,. 2011). Second, an academic title testifies to the cognitive capability, experience, and willingness to search actively for external knowledge, leverage various sources of knowledge (e.g., scientific journals, patents, conferences or personal contacts), and collaborate with external partners (Cockburn and Henderson, 1998;; Enkel et al., 2016; Fosfuri and Tribó, 2008; Muscio, 2007). Third, the pure identification of external knowledge does not increase a firm`s PACAP if it is not understood correctly and put in an appropriate organizational context. Higher educated people have both the required technical expertise as well as the linguistic capacity to understand the compressed and convoluted knowledge of patents, professional journals, and publications. In addition, better educated and trained employees are more likely to transfer new external knowledge to colleagues and thereby serve as intra-organizational knowledge multipliers (Ebers and Maurer, 2014; ter Wal et al., 2011).

H1d: *An inventor team with higher educated members increases a firm`s PACAP*

4.2.3 Inter-organizational R&D Collaboration and a Firm`s PACAP

Next to inventor-individual aspects, inter-organizational R&D collaboration is viewed as a determinant of a firm`s PACAP (Ebers and Maurer, 2014; Fosfuri and Tribó, 2008; Spithoven et al., 2011; Volberda et al., 2010), though Cohen and Levinthal (1990) argue that ACAP arises primarily internally. Analog to the positive relationship between the number of inventors and PACAP, a higher number of applicants should also be able to higher absorption of external knowledge for various reasons. First, R&D collaborating actors have a higher prior knowledge base and network of knowledge partners, which positively affects PACAP. Second, they tend to have more resources and benefit from R&D synergies, which enables them to invest more in external knowledge searches. Third, R&D collaboration confronts the patent applicants with alternative knowledge, skills, processes and technologies, which increases their PACAP as they have to be open to their environment and scrutinize their own established routines (Araújo Burcharth et al., 2015). In addition, this confrontation has the potential to increase their PACAP if it lowers the level of routinization (Jansen et al., 2005) and if it leads to a higher level of market and technology orientation (Lichtenthaler, 2016). Various studies (Ebers and Maurer, 2014; Fosfuri and Tribó, 2008; Spithoven et al., 2011; Vie et al., 2014) document the argument for a positive relationship between inter-organizational R&D collaboration and PACAP. Opposing arguments refer to a lack of managerial attention (Ghisetti et al., 2015; Kim et al., 2016), resource and time consuming activities such as trust building, monitoring, and additional communication (Ferreras-Méndez et al., 2016), an increased level of formalization (Jansen et al., 2005), or protective attitudes, misalignment of interests, and asymmetric information (Araújo Burcharth et al., 2015). However, these arguments are of minor relevance to my case as I examine patented R&D collaboration, which requires aligned targets, a certain level of trust, and efficient working modes.

H2a: *A higher number of co-patenting actors increase a firm's PACAP.*

Cultural diversity among co-patenting actors not only adds different perceptual views and already existing knowledge, which increases PACAP, but also facilitates the absorption of global market and technology trends through geographic and social proximity. Lichtenthaler (2016) stresses that knowing global technology leaders and upcoming market trends, having sufficient market knowledge, and being able to value market potentials are essential for PACAP. Furthermore, culturally diverse inventor teams have access to a broader knowledge network and avoid cognitive lock-ins (Crescenzi et al., 2016). Finally, the international footprint represents a kind of external openness that enables firms to overcome local search biases and the "not-invented-here" syndrome (Araújo Burcharth et al., 2015). I therefore assume that co-patenting actors located at different countries have a higher PACAP, especially with respect to foreign knowledge.

H2b: *A more culturally diverse network of co-patenting actors increases a firm's PACAP.*

A different type of "cultural diversity" is industry-university R&D collaboration, which is rated as an important determinant of PACAP (Cockburn and Henderson, 1998). The main explanation for this is the access for private firms to complementary, sometimes unpublished scientific knowledge of not yet matured technologies and processes. Universities (often in public ownership) carry out basic research projects with no or only limited commercial potential that private firms themselves would not undertake due to the high risks but on whose generated knowledge their further technological development depends. This is highly relevant in the development of renewable energy technologies. Secondly, as a consequence of the collaboration the employees of the private firms are trained for a more directed knowledge search and gain a deeper understanding of the academic knowledge and language, which enables them to include academic sources in their search activities and thereby increases a firm`s PACAP (Fabrizio, 2009). Third, a university`s international network and a broad research scope including various academic disciplines (e.g., chemistry, biology, engineering) have a positive effect on absorbing international and intersectoral knowledge flows. Nevertheless, challenges refer to the alignment of different knowledge sources and research types, difficulties in designing incentive mechanisms, absent trust and networking abilities as well as the cultural gap between academic knowledge publication and industrial knowledge disclosure (Fukugawa, 2013; Miller et al., 2016). However, there is substantial empirical evidence (Azagra-Caro et al., 2017; Belderbos et al., 2016; Dornbusch and Neuhäusler, 2015;

Kafouros et al., 2015; Wirsich et al., 2016;) that private firms access complementary knowledge from industry-university R&D collaboration, which positively affects PACAP.

H2c: *Industry-university R&D collaboration increases a firm`s PACAP.*

4.3 Methodology, Data Sample, and General Insights on Patenting Patterns and Knowledge Flows of the German PV Sector

4.3.1 Methodology of Patent-citation Analysis to Measure Knowledge Flows and PACAP

Although "knowledge flows… are invisible; they leave no paper trail by which they may be measured and tracked" (Krugman, 1991, p.53), patent citation analysis - pioneered by Jaffe et al. (1993) - is an established research method for measuring knowledge flows on a technological (e.g., Aharonson and Schilling, 2016; Battke et al., 2016; Nemet, 2012) and geographic level (e.g., Maggioni et al., 2011; Morescalchi et al., 2015; Murata et al., 2014) and is also applied to the energy sector (Braun et al. 2011; Wu, Mathews 2012; Bointner 2014; Guan, Liu 2016). Empirical patent studies in the context of ACAP are rare and primarily use patents as an outcome variable (Volberda et al., 2010), though patent and citation data directly correspond to the two subsets of ACAP described by Zahra and George (2002). Backward citation, i.e., the number of cited patents, meets the definition of PACAP for codified knowledge as patent laws force inventors to document their identified, analyzed, and understood relevant prior art. Patents themselves are the codified proof for RACAP. The transformation of acquired knowledge and its combination with existing knowledge in order to generate something new is required, as a patent demands a certain degree of novelty. The exploitation of knowledge towards commercial ends is the inner nature of a patent, which grants a firm the legal claim to generate economic benefits. Furthermore, research based on patent and citation data, which are reviewed by independent patent offices and examiners, satisfies the required high level of objectiveness for ACAP measurement (ter Wal et al., 2011) compared to survey-based analysis. Finally, patent data are publicly accessible and provide granular information about the inventor, patent holder, and technological characteristics, and possess a stable and hierarchical classification scheme and the ability to focus the research on specific technologies (Griliches 1990; Jaffe et al. 1993; Popp 2005a; Johnstone et al. 2010).

Limitations of patent citation analysis have been discussed widely. First, not all inventions are codified as a patent due to missing patentability or avoidance of information disclosure (Griliches, 1990). Second, citation data per definition neglect non-patented knowledge flows through, e.g., labor mobility, customer and supplier interaction, and conferences and trade fairs (Scherngell and Jansenberger, 2006). Third, self-citations and patenting for strategic motives have a negative impact on actual knowledge flows (Blind et al., 2006). Fourth, patent examiners and patent lawyers add or delete prior art during the application process (Alcácer and Gittelman, 2006; Criscuolo and Verspagen, 2008). Based on a survey, (Jaffe et al. 2000a) show that 38% of inventors possess knowledge about the cited inventions for their patents before or during their invention phase, a third of them gain knowledge after the invention, and a little less than one-third are not aware of the cited knowledge. Fifth, the information documented in a patent are a restricted source of information on an inventor (Jung and Ejermo, 2014) and international R&D collaboration (Bergek and Bruzelius, 2010). Finally, truncation biases as well as different levels of patent activity and technological progress over time make patent data an imperfect indicator (Jaffe et al., 1998). This paper addresses some of these limitations by using constant citation periods to reduce truncation biases (Nemet, 2012), cautiously deleting self-citations, and defining intra-sectoral knowledge flows through simple binary variable, which leaves space for misclassification. Finally, I limit my empirical analysis (Section 4) to the years 2006–2015 so as to achieve a period of stable patent and knowledge conditions.

4.3.2 Data Collection and Clearance

Using business directories, insolvency registers, and press research, I establish a sample of 596 firms for the German PV sector. In order to identify the patenting firms, I enter the firm names into the Derwent Innovation Index, which records patent application data from 40 global patent offices. Simultaneously, I apply a search filter for PV patents based on relevant technological keywords and International Patent Classification (IPC) codes from previous studies (Corsatea, 2014; Johnstone et al., 2010) as some sample firms operate outside the PV sector. After deleting duplicate values, I enter the patent application data into the European Patent office database to download the backward and forward citation data and delete self-citations, i.e., equal applicants for the initial and cited/citing patents. Finally, I manually remove individual applicants listed together with their firms as patent holders and exclude duplicate values of nationalities and IPC codes. My final database for analyzing patent activity and knowledge flows (Section 3.3) covers the years 1976–2015 and consists of 148 German PV firms with at least one patent application, 1,782 patent applications with 8,573 cited and 5,210 citing patents. The database for my empirical analysis (Section 4) is limited to the years 2006–2015 and covers 129 patenting firms with a total of 1,446 patent applications and 7867 cited patents.

4.3.3 General Observations on Patenting Patterns and Knowledge Flows in the German PV Sector

Table 14 clusters the patent applications of the German PV sector on a five-year-scale and provides five insightful results. First, the number of PV patent applications reaches a first peak in the early 1980s in reaction to the second oil crisis in Germany and has grown intensively since the mid-1990s due to the Kyoto Protocol and associated environmental policies (Johnstone et al., 2010). The increasing number of German PV firms with at least one patent application confirms this positive development until 2011, when international competition, a decrease in public funding policies, and consolidation tendencies cause a downturn in the German PV sector. Second, and most importantly, to underline the relevance of a firm`s PACAP, inventors depend more heavily on external knowledge as the number of cited patents has increased over time to 5.49 patents today. In addition, they have to oversee a knowledge base of almost a decade (average citation lag of 9.06 years). Third, larger and more diverse inventor teams have gained momentum as the average number of inventors per patent has grown steadily and reached a recent climax of 2.88 inventors (in line with Crescenzi et al. (2016)). The participation of female inventors is almost non-existent until the mid-1990s, reaching a peak between 1996–2005, dropping later, and now re-gaining momentum; however, EUROSTAT data show that Germany still has the second smallest participation rate of female researchers in the business enterprise sector among EU-countries, with 14.1% in 2013 (the average for EU-countries is 20.0%)[6]. Fourth, co-patenting initiatives among private firms as well as with universities have decreased in recent years. Industrial co-patenting activities were highest between 2001–2005, with 1.66 applicants. Industry-university co-patenting activities did not exist until the mid-1990s and remain with 3.37% at a marginal level, which can be explained by only few universities engaging in academic entrepreneurship, the necessity of diverse knowledge sources, relatively limited research funds, and huge competition from private firms (Han and Niosi, 2016). Fifth, the results indicate the substantial role of governmental R&D

[6] Source: Eurostat database; Share of female researchers by sectors of performance (rd_p_femres), accessed: 26.04.2017

funding in the development of PV technologies as over half of the patents are applied when one of the applicant firms receives a public R&D grant.

Period	No. of patents	No. of PV firms[7]	Avg. No. of cited patents	Avg. citation lag of cited patents (years)	Avg. No. of invent-tors	Female partici-pation[8] (%)	Avg. No. of applicants	Ind.-univ. R&D colla-boration[9] (%)	Public R&D funding[10] (%)
1976-1980	20	2	1.00	5.10	1.22	0.00	1.00	0.00	45.00
1981-1985	65	3	2.65	6.75	2.19	3.51	1.00	0.00	98.46
1986-1990	43	3	1.65	5.94	1.85	0.00	1.02	0.00	95.35
1991-1995	32	5	1.53	8.88	2.55	0.00	1.38	0.00	81.25
1996-2000	55	18	1.96	10.85	2.76	26.83	1.56	3.64	34.55
2001-2005	121	37	2.36	9.91	2.82	27.16	1.66	5.79	39.67
2006-2010	501	115	5.35	10.20	2.81	13.83	1.33	3.79	49.50
2011-2015	945	82	5.49	8.43	2.88	16.88	1.18	3.39	54.71
1976-2015	**1,782**	**148**	**4.81**	**9.06**	**2.79**	**15.71**	**1.26**	**3.37**	**54.55**

Table 14: Descriptive Statistics on Patent Activity and Patterns in the German PV Sector, 1976-2015

Table 15 highlights the importance of international knowledge flows in the German PV sector as 58.19% of all cited patents derive from foreign firms and arise from a growing number of foreign countries with a current high of 31. USA and Japan are the most important knowledge sources for German PV firms, which reflects their historical leadership role in renewable energy technologies (Bointner 2014; Binz et al. 2017) and that technological rather than geographic proximity determines knowledge exchange. However, international knowledge flows are not a one-sided phenomenon as 48.51% of all citing patents refer to foreign firms, with a present peak of 37 countries. Once again, USA and Japan absorb most of the knowledge, followed by France, China and South Korea. Interestingly, the steadily decreasing share of the Top 5 cited and citing countries confirms an increasing geographic diversification of knowledge flows. This

7 Number of German PV firms with at least one patent in the corresponding period
8 Share of patents with at least one female inventor (%)
9 Share of patents, where at least one of the applicants is a university or research institute (%)
10 Share of patents, where at least one of the applicant firms receives public R&D funding (%)

interim result documents how important it is for firms to build up PACAP accordingly to absorb foreign knowledge and be able to compete in a globalized environment.

	Incoming knowledge flows (cited patents)			Outgoing knowledge flows (citing patents)		
Period	**Share foreign patents [11] (%)**	**No. of count-ries**	**Top 5 countries (% of foreign patents)**	**Share foreign patents [12] (%)**	**No. of count-ries**	**Top 5 countries (% of foreign patents)**
1976-1980	63.16	4	US (75.00), FR (8.33), JP (8.33), UA (8.33), -	100.00	1	US (100.00), -
1981-1985	53.75	11	US (60.47), JP (11.63), FR (8.14), NL (5.81), IT (3.49)	36.17	6	US (58.82), JP (26.47), CN (5.88), BR (2.94), FR (2.94)
1986-1990	49.25	7	US (45.45), JP (27.27), FR (9.09), LU (6.06), NL (3.03)	35.62	5	US(46.15), JP (26.92), FR (11.54), GB (11.54), IT (3.85)
1991-1995	61.70	6	US (55.17), JP (20.69), FR (6.90), AU (6.90), NL (3.45)	58.57	7	JP (63.41), US (14.63), FR (7.32), AT (4.88), CA (4.88)
1996-2000	59.26	7	JP (45.31), US (40.63), FR (6.25), NL (3.13), CA (1.56)	44.66	13	JP (34.78), US (15.22), FR (10.87), AT (8.70), NL (8.70)
2001-2005	77.95	13	US (53.20), JP (37.04), NL (2.02), FR (1.68), CH (1.68)	56.64	11	US (39.51), JP (29.63), FR (11.11), AT (4.94), NL (4.94)
2006-2010	65.56	26	US (56.27), JP (29.27), NL (1.92), GB (1.92), FR (1.71)	53.72	27	US (55.73), JP (11.28), FR (4.96), KR (3.59), AT (3.25)
2011-2015	52.88	31	US (42.01), JP (33.24), CH (4.40), KR (3.34), GB (2.59)	47.14	37	US (33.83), CN (12.84), JP (11.41), FR (9.00), KR (5.62)
1976-2015	**58.19**	**34**	**US (48.32), JP (31.63), CH (2.96), GB (2.22), KR (2.20)**	**48.51**	**39**	**US (38,46), JP (13,52), CN (9,41), FR (8,30), KR (4,80)**

Table 15: Analysis of International Incoming and Outgoing Knowledge Flows in the German PV Sector, 1976-2015

Figures 6 and 7 illustrate the same analysis on a yearly basis for a regional aggregation of countries.

11 Share of cited patents with at least one non-German applicant (%)
12 Share of citing patents with at least one non-German applicant (%)

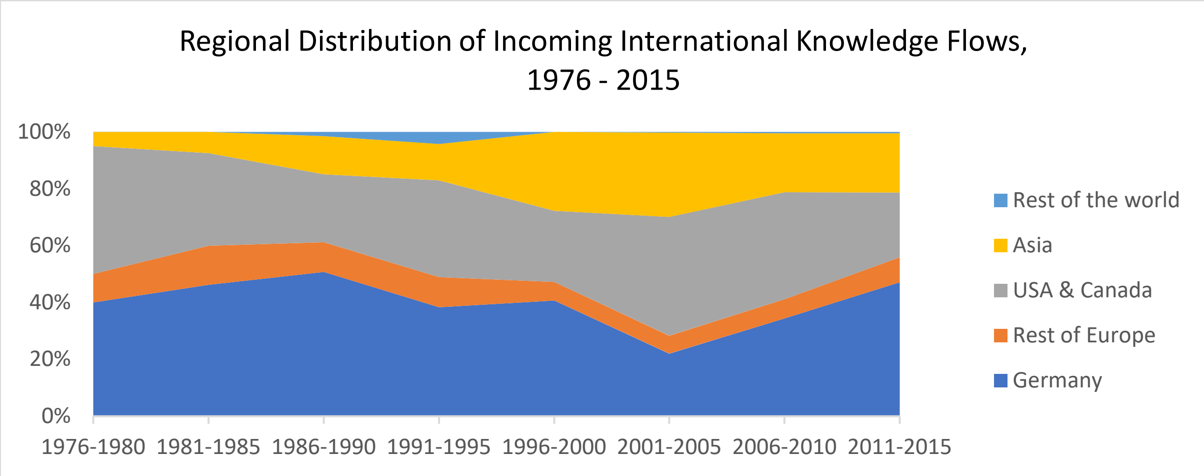

Figure 6: Regional Distribution of Incoming International Knowledge Flows based on Cited Patents, 1976-2015[13]

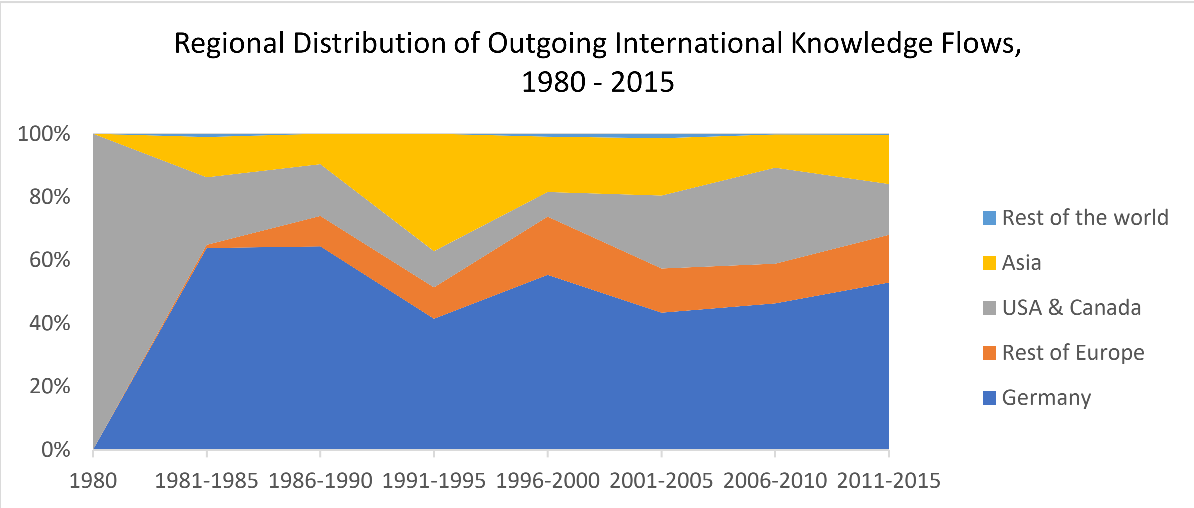

Figure 7: Regional Distribution of Outgoing International Knowledge Flows based on Citing Patents, 1980-2015[14]

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[13] Rest of Europe includes Austria, Belgium, Cyprus, Denmark, Finland, Greece, Ireland, Iceland, Italy, Liechtenstein, Luxembourg, Netherlands, Norway, Poland, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom
Asia includes China, Hong Kong, Israel, India, Japan, Russia, South Korea, Taiwan
Rest of the world includes Australia, Barbados, South Africa

[14] Rest of Europe includes Austria, Belgium, Czech Republic, Denmark, Finland, France, Greece, Iceland, Italy, Liechtenstein, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Switzerland, Sweden, United Kingdom
Asia includes China, Hong Kong, Israel, India, Japan, Russia, Singapore, South Korea, Taiwan, Thailand, Turkey, Uzbekistan
Rest of the world includes Australia, Brazil, British Virgin Islands

Table 16 shows the importance of external knowledge in terms of intersectoral knowledge flows for the German PV sector as well as its broad applicability to other sectors (for detailed information on sector specific IPC codes see Table 17). About half of the cited patents (49.21%) come from outside the PV sector (applying the categorization of Corsatea (2014) and Johnstone et al. (2010), and relate mainly to semiconductor and electrical solid state devices (H01L), luminescent materials (C09K11), and electroluminescent light sources (H05B33). Almost half of the citing patents (46.97%) refer to technological fields outside the PV sector. Interestingly, four of the five most cited IPC codes are among the most citing ones, which shows that intersectoral knowledge flows are a two-sided phenomenon rather than a single-sided dependency.

Period	Incoming knowledge flows (cited patents): Share non-PV patents [15] (%)	Incoming: Top 5 categories (% of Non-PV patents)	Outgoing knowledge flows (citing patents): Share non-PV patents[15] (%)	Outgoing: Top 5 categories (% of Non-PV patents)
1976-1980	40.00	H01L21 (21.67), H01L29 (15.00), C23C16 (11.67), C30B29 (6.67), H01L (6.67)	24.29	H01L21 (16.42), C30B29 (14.93), C30B11 (7.46), C30B15 (7.46), C30B1 (5.97)
1981-1985	31.76	H01L21 (17.07), C30B15 (9.09), C30B29 (8.87), C01B33 (7.76), B01J (5.10)	26.32	C30B29 (11.01), C30B15 (9.75), H01L21 (7.22), C01B33 (7.04), C30B11 (6.32)
1986-1990	28.17	H01L21 (16.99), C01B33 (10.46), C30B29 (7.84), C30B15 (5.23), H01L23 (5.23)	29.36	H01L21 (9.24), B23K26 (7.61), C30B29 (4.35), C30B15 (4.35), H01L23 (3.80)
1991-1995	20.41	H01L21 (10.67), F24J3 (10.67), H01L25 (5.33), H01L29 (4.00), B23K26 (4.00)	28.28	H01L21 (8.90), H02J3 (7.33), F24F5 (5.24), C03C3 (4.71), E06B9 (4.19)
1996-2000	22.43	H01L21 (8.17), H01L29 (4.81), H02J7 (4.81), C23C14 (3.37), H01L25 (2.50)	30.97	H01L21 (7.50), H01L51 (4.06), H02J7 (3.44), C30B11 (3.44), C30B29 (2.19)
2001-2005	60.99	C03C3 (7.83), H01L21 (4.49), H01L51 (4.36), G02F1 (3.59), G09F9 (3.47)	62.04	H01L51 (18.20), C09K11 (9.79), C08G61 (4.28), H05B33 (3.41), H01L21 (2.90)
2006-2010	49.32	H01L51 (6.99), H01L21 (6.13), C09K11 (4.66), H05B33 (3.57), C08G61 (3.04)	46.00	H01L51 (12.50), H01L21 (5.70), C09K11 (4.86), F16M13 (2.38), G01R31 (2.35)
2011-2015	50.38	H01L51 (8.84), C09K11 (5.68), H01L21 (4.80), H05B33 (3.87), C08G61 (2.75)	53.14	H01L51 (10.20), H02J3 (5.82), H01L21 (4.86), C09K11 (4.74), G01R31 (3.54)
1976-2015	**49.21**	H01L51 (7.54%), H01L21 (5.80), C09K11 (4.83), H05B33 (3.48), C08G61 (2.60)	**46.97**	H01L51 (11.08), H01L21 (5.63), C09K11 (4.89), H02J3 (2.39), C08G61 (2.23)

Table 16: Analysis of Intersectoral Incoming and Outgoing Knowledge Flows in the German PV Sector, 1976-2015

15 Share of cited patents not classified as a PV patent based on Johnstone et al. (2010) and Corsatea (2014)

IPC code	Description
B01J	Chemical or physical processes, e.g. catalysis, colloid chemistry, their relevant apparatus
B23K26	Working by laser beam, e.g. welding, cutting or boring
C01B33	Silicon; compounds thereof
C03C3	Glass compositions
C08G61	Macromolecular compounds obtained by reactions forming a carbon-to-carbon link in the main chain of the macromolecule
C09K11	Luminescent, e.g. electroluminescent, chemiluminescent materials
C23C14	Coating by vacuum evaporation, by sputtering or by ion implantation of the coating forming material
C23C16	Chemical coating by decomposition of gaseous compounds, without leaving reaction products of surface material in the coating, i.e. chemical vapour deposition (CVD) processes
C30B1	Single-crystal growth directly from the solid state
C30B11	Single-crystal-growth by normal freezing or freezing under temperature gradient, e.g. Bridgman-Stockbarger method
C30B15	Single-crystal growth by pulling from a melt, e.g. Czochralski method
C30B29	Single crystals or homogeneous polycrystalline material with defined structure characterized by the material or by their shape
E06B9	Screening or protective devices for openings, with or without operating or securing mechanisms; Closures of similar construction
F16M13	Other supports for positioning apparatus or articles
F24F5	Air-conditioning systems or apparatus not covered by F24F 1/00 or F24F 3/00
F24J3	Other production or use of heat, not derived from combustion
G01R31	Arrangements for testing electric properties; Arrangements for locating electric faults; Arrangements for electrical testing characterized by what is being tested not provided for elsewhere
G02F1	Devices or arrangements for the control of the intensity, color, phase, polarization or direction of light arriving from an independent light source, e.g. switching, gating or modulating; Non-linear optics
G09F9	Indicating arrangements for variable information in which the information is built-up on a support by selection or combination of individual elements
H01L	Semiconductor devices; electric solid state devices not otherwise provided for
H01L21	Processes or apparatus adapted for the manufacture or treatment of semiconductor or solid state devices or of parts thereof
H01L23	Details of semiconductor or other solid state devices
H01L25	Assemblies consisting of a plurality of individual semiconductor or other solid state devices
H01L29	Semiconductor devices adapted for rectifying, amplifying, oscillating or switching and having at least one potential-jump barrier or surface barrier
H01L51	Solid state devices using organic materials as the active part, or using a combination of organic materials with other materials as the active part; Processes or apparatus specially adapted for the manufacture or treatment of such devices, or of parts thereof
H02J3	Circuit arrangements for ac mains or ac distribution networks
H02J7	Circuit arrangements for charging or depolarizing batteries or for supplying loads from batteries
H05B33	Electroluminescent light sources

Table 17: Top 5 IPC Codes of Incoming and Outgoing Intersectoral Knowledge Flows[16]

[16] Source: https://worldwide.espacenet.com/classification (Classification website of the European Patent Office, accessed latest April 2017

4.4 Empirical Application and Results

4.4.1 Model and Description of Variables

To test the hypotheses outlined in Sections 2.2 and 2.3, I assume that a higher count of cited "external patents," i.e., exclusive self-citations, reflects a higher firm`s PACAP for codified knowledge, as cited "external patents" document identified, valued, acquired, and assimilated external knowledge. The publicness of patent data and the use of patent search in practice (Enkel and Heil, 2014) confirm the legitimacy of my approach. All German PV firms are thus generally able to absorb external codified knowledge via patents, and differences in a firm`s PACAP can be assigned to inventor-related (Hypothesis 1), inter-organizational (Hypothesis 2), or eco-systematic factors. To operationalize my model, I use a negative binomial regression model as the dependent variables are count outcomes, and I observe overdispersion. Negative binomial regression models are a less restrictive form of Poisson regression models and allow the mean and variance to vary (Hausman et al. 1984). I run three separated models to account for external knowledge flows in general (Model 1), international knowledge flows (Model 2), and intersectoral knowledge flows (Model 3). The unit of analysis for all three models is patent application level, the analysis period is 2006–2015, and the constant citation window is 10 years as this is close to the average citation lag of 9.04 years for 2006–2015 (9.06 years for 1976–2015).

Dependent variable

Total external knowledge flows (Model 1). Count of total cited patents per patent application represents total external knowledge flows.

Foreign knowledge flows (Model 2). Count of cited patents with at least one non-German patent applicant firm characterizes foreign knowledge flows.

Non-PV knowledge flows (Model 3). Count of cited patents whose technological components are not categorized to a PV-sector related IPC code determines intersectoral knowledge flows (based on Corsatea, 2014; Johnstone et al., 2010).

Independent variables

Inventor-related independent variables

Count inventor. Based on the patent information, I extract the variable *count of inventor* as a first indication of whether the number and diversity of inventors is a driver for PACAP (Hypothesis 1a).

Cultural diversity inventor. I count the different inventor´s home countries to operationalize cultural diversity (Hypothesis 1b).

Gender diversity inventor. The variable *gender diversity inventor* takes the value 1 if at least one inventor is female and 0 for otherwise. The variable is marked as “missing” in the case of missing inventor information and if the given name allows for both female and male interpretations (Hypothesis 1c).

Education inventor. The variable *education inventor* is 1 if at least one inventor is a graduated engineer (German academic title: “Diplom-Ingeniuer”) or holds a doctor title and 0 for otherwise (Hypothesis 1d).

Inter-organizational independent variables

Count applicant. The count of listed patent applicant firms (i.e. excluding individuals) serves as a first indicator of R&D inter-organizational effects on PACAP (Hypothesis 2a).

Cultural diversity applicant. I count the different applicant firms' home countries to operationalize cultural diversity. The applicant`s home country is added from the corporate websites in the case of missing data (Hypothesis 2b).

Industry-university R&D collaboration. This binary variable takes the value 1 if a university or research institute is listed among the patent applicants and 0 for otherwise (Hypothesis 2c).

Control variables

Spatially proximate PV-firms. I control for the number of spatially proximate PV-firms as a higher density of PV firms facilitates local knowledge flows across competitors, suppliers, and customers. In addition, it increases competition, which leads firms to invest in knowledge search and their own R&D capabilities, both of which have a positive effect on PACAP. To operationalize these effects, the initial sample of 596 PV firms along the whole PV value chain (including firms with and without patents) is distributed according to the first two digits of its German 5-digit zip-code. In the case of two or more domestic applicants per patent, I took the average number of spatially proximate PV firms.

Spatially proximate universities. In the same manner, I map the number of universities to the patenting PV firms to account for the existence of local knowledge spillovers between universities and industry (Autant-Bernard et al., 2013; Azagra-Caro et al., 2017; Fukugawa, 2013; Miller et al., 2016). Positive effects of spatially proximate universities on a firm`s

PACAP refer to formal open lab programs and a variety of informal channels, e.g., personal contacts, conferences, collaboration with graduates, reading of local scientific papers and patents (Azagra-Caro et al., 2017). Interestingly, for the absorption of foreign knowledge, Edler et al. (2011) show that scientists participating in temporary cross-border research activities contribute to knowledge transfer activities of both their host and home countries.

Governmental ties. I download the direct public R&D funding periods per firm from the German Federal Ministry for Environment, Nature Conservation, Building and Nuclear Safety (2006 to 2013), and the German Federal Ministry for Economic Affairs and Energy (2014 and 2015). This data allows me to operationalize a firm`s governmental relationship, which enables them to build up knowledge networks. The binary variable is 1 if one of the applicant firms receives public R&D funding and 0 for otherwise.

Patent office. I control for different patent offices as the necessity and possibility to add prior art depends on (supra-) national patent laws (Scherngell and Jansenberger, 2006) as well as patent examiner behavior (Alcácer and Gittelman, 2006).

Priority date. To account for the cumulative nature of knowledge and reflect changes in patenting intensity and legislation (Nemet, 2012), I control for a patent`s priority date, which is the date closest to its invention (Braun et al., 2011).

Patent scope. The variable patent scope, i.e., the count of listed IPC codes, accounts for technological differences. A “broader patent” refers to a higher technological connectivity to other IPC codes and might therefore have a greater rate of backward citations.

4.4.2 Empirical Results

Tables 18 and 19 show the descriptive statistics and correlation matrix. The dependent variables are not highly correlated with any of the independent variables. A high and logical correlation exists between the independent variables *count applicant* and *cultural diversity applicant* (r=0.51) as well as between *spatially proximate PV firms* and *spatially proximate universities* (r=0.59), reflecting the positive relationship between the economic and academic status of certain regions in Germany.

	N	Mean	S. D.	Min	Max
Dependent variable knowledge flows (kf)					
Total kf (Model 1)	1,446	3.97	6.33	0	64
Foreign kf (Model 2)	1,446	2.22	4.47	0	56
Non-PV kf (Model 3)	1,446	2.11	5.63	0	64
Inventor-related independent variables (Hypothesis 1)					
Count inventor	1,272	2.86	1.92	1	25
Cultural diversity inventor	1,272	1.09	0.32	1	4
Gender diversity inventor	1,259	0.16	0.37	0	1
Education inventor	1,272	0.02	0.14	0	1
Inter-organizational independent variables (Hypothesis 2)					
Count applicant	1,446	1.23	0.49	1	4
Cultural diversity applicant	1,446	1.06	0.24	1	3
Ind.-univ. R&D collaboration	1,446	0.02	0.14	0	1
Control variables					
Spatially proximate PV firms	1,446	11.42	6.10	2	21
Spatially proximate universities	1,446	6.22	4.43	0	27
Governmental ties	1,446	0.53	0.50	0	1
Patent office	1,446	1.39	3.14	0	19
Priority date	1,446	2011.21	2.15	2006	2015
Patent scope	1,446	5.50	4.63	1	50

Table 18: Descriptive Statistics of Dependent and Independent Variables (10-Year Citation Window)

		1	2	3	4	5	6	7	8	9	10
1	Total knowledge flows	1.00									
2	Foreign knowledge flows	0.89	1.00								
3	Non-PV knowledge flows	0.91	0.75	1.00							
4	Count inventor	0.15	0.13	0.15	1.00						
5	Cultural diversity inventor	0.09	0.15	0.05	0.23	1.00					
6	Count applicant	0.00	0.08	-0.04	0.09	0.14	1.00				
7	Cultural diversity applicant	0.09	0.21	0.03	0.07	0.26	0.51	1.00			
8	Sp. proximate PV firms	-0.12	-0.09	-0.17	-0.12	-0.08	-0.04	-0.12	1.00		
9	Sp. proximate universities	0.01	-0.02	-0.04	-0.08	-0.08	-0.01	-0.04	0.59	1.00	
10	Patent scope	0.39	0.28	0.46	0.17	0.08	0.11	0.12	-0.22	-0.06	1.00

Table 19: Correlation Matrix (N=1,272)

Table 20 provides the empirical results of the outlined independent variables on a firm`s PACAP for external knowledge in general (Model 1), foreign knowledge (Model 2), and knowledge from outside the PV sector (Model 3).

	Model 1 **Total kf**[17]	**Model 2** **Foreign kf**[17]	**Model 3** **Non-PV kf**[17]
Inventor-related ind. variables (Hypothesis 1)			
Count inventor	0.0436***	0.0470**	0.0631**
	(0.0161)	(0.0193)	(0.0250)
Cultural diversity inventor	0.105	0.199**	0.0352
	(0.0878)	(0.0981)	(0.140)
Gender diversity inventor	0.270***	0.144	0.364***
	(0.0798)	(0.0927)	(0.126)
Education inventor	0.160	0.175	0.409
	(0.201)	(0.234)	(0.320)
Inter-organizational ind. variables (Hypothesis 2)			
Count applicant	-0.171**	-0.143*	-0.375***
	(0.0676)	(0.0781)	(0.106)
Cultural diversity applicant	0.352**	0.470***	0.490*
	(0.159)	(0.172)	(0.278)
Ind.-univ. R&D collaboration	0.553***	0.594***	0.342
	(0.204)	(0.224)	(0.335)
Control variables			
Spatially proximate PV firms	-0.0189***	-0.0123*	-0.0254**
	(0.00615)	(0.00715)	(0.0102)
Spatially proximate universities	0.0343***	0.0203**	0.0286*
	(0.00793)	(0.00937)	(0.0152)
Governmental ties	-0.0639	0.0877	0.00782
	(0.0631)	(0.0743)	(0.104)
Patent office	YES	YES	YES
Priority date	YES	YES	YES
Patent scope	0.0617***	0.0558***	0.110***
	(0.00589)	(0.00670)	(0.00998)
Constant	0.0639	-0.669**	-1.536***
	(0.291)	(0.328)	(0.511)
Observations	1,259	1,259	1,259
log likelihood	-3,053.21	-2,444.11	-2,208.54
LR chi2	367.09	344.15	379.57
Prob>chi2	0.0000	0.0000	0.0000
Standard errors in parentheses			
*** p<0.01, ** p<0.05, * p<0.1			

Table 20: Empirical Results for Negative Binomial Regression Models (10-Year Citation Window)

[17] kf = knowledge flows

The empirical results fully support Hypothesis 1a and imply that a higher number of inventors increase a firm`s PACAP for all three knowledge dimensions. Interestingly, the cultural diversity of the inventors (Hypothesis 1b) is only significant for absorbing knowledge from foreign firms (Model 2). For Hypothesis 1c, the findings provide evidence for a significant positive effect of gender diversity on a firm`s PACAP as it is highly significant and positive for Models 1 and 3. For foreign knowledge flows (Model 2), the results are not significant for the 10 year-horizon of cited patents shown above, but for a 15 year-horizon (see Table 21). Finally, I fail to confirm Hypothesis 1d as there is no empirical evidence for a significant positive relation between inventor teams with higher educated members and a firm`s PACAP.

	Total knowledge flows (Model 1)				Foreign knowledge flows (Model 2)				Non-PV knowledge flows (Model 3)			
	Infinite	15 years	10 years	5 years	Infinite	15 years	10 years	5 years	Infinite	15 years	10 years	5 years
Inventor-rel. IV (H1)												
Count inventor	0.0469***	0.0429***	0.0436***	0.0111	0.0555***	0.0445**	0.0470**	0.0271	0.0611**	0.0555**	0.0631**	0.0321
	(0.0160)	(0.0159)	(0.0161)	(0.0170)	(0.0185)	(0.0189)	(0.0193)	(0.0210)	(0.0250)	(0.0250)	(0.0250)	(0.0257)
Cult. diversity inventor	0.0988	0.105	0.105	0.156*	0.210**	0.215**	0.199**	0.228**	0.103	0.0835	0.0352	0.0345
	(0.0871)	(0.0867)	(0.0878)	(0.0884)	(0.0962)	(0.0967)	(0.0981)	(0.104)	(0.140)	(0.140)	(0.140)	(0.139)
Gender diversity inventor	0.226***	0.261***	0.270***	0.144*	0.100	0.151*	0.144	0.111	0.303**	0.355***	0.364***	0.130
	(0.0791)	(0.0785)	(0.0798)	(0.0810)	(0.0899)	(0.0906)	(0.0927)	(0.101)	(0.126)	(0.127)	(0.126)	(0.127)
Education inventor	0.107	0.160	0.160	0.0883	0.0735	0.140	0.175	0.224	0.279	0.370	0.409	0.209
	(0.197)	(0.197)	(0.201)	(0.206)	(0.225)	(0.228)	(0.234)	(0.252)	(0.316)	(0.320)	(0.320)	(0.330)
Inter-organiz. IV (H 2)												
Count applicant	-0.166**	-0.167**	-0.171**	-0.112	-0.133*	-0.133*	-0.143*	-0.0922	-0.395***	-0.355***	-0.375***	-0.335***
	(0.0658)	(0.0660)	(0.0676)	(0.0685)	(0.0744)	(0.0758)	(0.0781)	(0.0846)	(0.104)	(0.105)	(0.106)	(0.109)
Cult. diversity applicant	0.221	0.288*	0.352**	0.423***	0.259	0.386**	0.470***	0.529***	0.317	0.440	0.490*	0.533**
	(0.157)	(0.157)	(0.159)	(0.155)	(0.170)	(0.170)	(0.172)	(0.178)	(0.281)	(0.283)	(0.278)	(0.260)
Ind.-univ R&D collab.	0.706***	0.615***	0.553***	0.431**	0.774***	0.679***	0.594***	0.521**	0.748**	0.625*	0.342	0.151
	(0.205)	(0.202)	(0.204)	(0.199)	(0.224)	(0.222)	(0.224)	(0.231)	(0.345)	(0.339)	(0.335)	(0.324)
Control variables												
Sp. proximate PV firms	-0.0186***	-0.0226***	-0.0189***	-0.0149**	-0.0124*	-0.0181***	-0.0123*	-0.00653	-0.0250**	-0.0293***	-0.0254**	-0.0243**
	(0.00600)	(0.00601)	(0.00615)	(0.00622)	(0.00684)	(0.00695)	(0.00715)	(0.00776)	(0.0101)	(0.0102)	(0.0102)	(0.0102)
Sp. proximate	0.0314***	0.0356***	0.0343***	0.0265***	0.0203**	0.0228**	0.0203**	0.0109	0.0243	0.0295*	0.0286*	0.0227
Universities	(0.00778)	(0.00782)	(0.00793)	(0.00777)	(0.00895)	(0.00916)	(0.00937)	(0.0101)	(0.0152)	(0.0153)	(0.0152)	(0.0147)
Governmental ties	-0.0773	-0.0611	-0.0639	-0.0966	0.0412	0.0714	0.0877	0.0398	-0.0330	-0.00213	0.00782	-0.0555
	(0.0614)	(0.0618)	(0.0631)	(0.0638)	(0.0706)	(0.0723)	(0.0743)	(0.0807)	(0.102)	(0.103)	(0.104)	(0.104)
Patent office	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Priority date	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Patent scope	0.0605***	0.0631***	0.0617***	0.0453***	0.0557***	0.0572***	0.0558***	0.0377***	0.108***	0.111***	0.110***	0.0885***
	(0.00588)	(0.00580)	(0.00589)	(0.00571)	(0.00663)	(0.00658)	(0.00670)	(0.00715)	(0.0101)	(0.0100)	(0.00998)	(0.00958)
Constant	0.595**	0.306	0.0639	-0.279	-0.0298	-0.410	-0.669**	-0.998***	-0.621	-1.183**	-1.536***	-1.581***
	(0.280)	(0.284)	(0.291)	(0.294)	(0.312)	(0.321)	(0.328)	(0.345)	(0.476)	(0.495)	(0.511)	(0.497)
Observations	1,259	1,259	1,259	1,259	1,259	1,259	1,259	1,259	1,259	1,259	1,259	1,259
log likelihood	-3,410.19	-3,192.62	-3,053.21	-2,569.78	-2,856.82	-2,600.93	-2,444.11	-1,973.24	-2,559.05	-2,356.99	-2,208.54	-1,766.81
LR chi2	383.62	400.45	367.09	222.34	371.56	371.29	344.15	257.95	394.99	403.06	379.57	246.85
Prob>chi2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 21: Negative Binomial Regression Models for Citation Windows of Infinite, 15, 10 and 5 Years

A key insight is the missing support for Hypothesis 2a, which is, at first glance, counterintuitive. According to the empirical results, a higher number of applicants per patent reduce their PACAP in all three models. In contrast and as predicted in Hypothesis 2b, the cultural diversity of applicants increases their PACAP at a significant level for all three knowledge dimensions. Industry-university R&D collaboration enables PV firms to gather additional external knowledge, which confirms Hypothesis 2c for Models 1 and 2. For Model 3, Hypothesis 2c is significantly positive for an infinite and 15 year-horizon (see Table 21).

The empirical results of the control variables are also of interest. In contrast to my argumentation for a positive impact of *spatially proximate PV firms*, a firm´s PACAP decreases with the number of surrounding PV firms at a significant level. This finding runs parallel with the rejection of Hypothesis 2a and shows that a higher number of co-patenting members of formal (estimated by *count applicant*) and potentially informal R&D collaboration (estimated by *spatially proximate PV firms)* decrease PACAP. The significant positive effect of *spatially proximate universities* for a firm's PACAP confirms the important role of universities within regional innovation systems and reinforces the positive effect of industry-university knowledge exchange on PACAP, as already tested with Hypotheses 2c for a formal R&D collaboration. There is no empirical evidence that *governmental ties* enable access to a broader knowledge base. The control variable *patent office* is hardly significant, while *priority date* is significantly positive for Models 1 and 3, which confirms the cumulative nature of knowledge. The highly significant positive sign of *patent scope* indicates that the number of cited knowledge increases with the applicability of the patent for various IPC codes.

4.4.3 Robustness-checks

In addition to the presented regression model, I calculate further regression specifications as robustness-checks. First, I control for truncation biases and vary the citation window from ten years (close to the average citation window of 9.06 years) to infinite, fifteen, and five years. The main results from the previous section are confirmed, with a minor significance for the 5 year window (see Table 21). Second, I apply a different estimation technique using Poisson regression models instead of negative binomial ones and receive stable results (see Table 22).

	Total knowledge flows (Model 1)				Foreign knowledge flows (Model 2)				Non-PV knowledge flows (Model 3)			
	Infinite	**15 years**	**10 years**	**5 years**	**Infinite**	**15 years**	**10 years**	**5 years**	**Infinite**	**15 years**	**10 years**	**5 years**
Inventor-rel. IV (H1)												
Count inventor	0.0378**	0.0370**	0.0389**	0.00674	0.0399**	0.0346*	0.0384**	0.0231	0.0396	0.0387	0.0484*	0.0168
	(0.0162)	(0.0173)	(0.0173)	(0.0153)	(0.0171)	(0.0187)	(0.0184)	(0.0179)	(0.0273)	(0.0295)	(0.0284)	(0.0252)
Cult. diversity inventor	0.126	0.106	0.105	0.178	0.280**	0.267**	0.250**	0.299***	0.103	0.0524	-0.0861	-0.0136
	(0.127)	(0.126)	(0.120)	(0.118)	(0.122)	(0.116)	(0.112)	(0.111)	(0.185)	(0.190)	(0.176)	(0.154)
Gender diversity inventor	0.309***	0.336***	0.331***	0.187*	0.200	0.245*	0.226*	0.195*	0.457***	0.490***	0.443***	0.183
	(0.111)	(0.109)	(0.105)	(0.0958)	(0.131)	(0.126)	(0.121)	(0.117)	(0.168)	(0.165)	(0.157)	(0.138)
Education inventor	0.0791	0.103	0.0912	0.0690	0.0833	0.130	0.142	0.229	0.0836	0.0991	0.0615	0.120
	(0.144)	(0.160)	(0.158)	(0.174)	(0.165)	(0.177)	(0.182)	(0.218)	(0.298)	(0.313)	(0.323)	(0.321)
Inter-organiz. IV (H 2)												
Count applicant	-0.251***	-0.234**	-0.225**	-0.141	-0.247**	-0.228*	-0.222*	-0.157	-0.494***	-0.431**	-0.375**	-0.284
	(0.0929)	(0.0969)	(0.101)	(0.102)	(0.118)	(0.127)	(0.133)	(0.136)	(0.182)	(0.192)	(0.188)	(0.199)
Cult. diversity applicant	0.373**	0.378**	0.422***	0.479***	0.484***	0.539***	0.615***	0.671***	0.467**	0.422*	0.302	0.418**
	(0.152)	(0.150)	(0.148)	(0.150)	(0.160)	(0.157)	(0.159)	(0.172)	(0.220)	(0.216)	(0.204)	(0.188)
Ind.-univ R&D collab.	0.820***	0.664**	0.602*	0.486*	0.963***	0.791***	0.706**	0.616**	1.178***	0.979**	0.724*	0.488
	(0.308)	(0.315)	(0.310)	(0.288)	(0.287)	(0.307)	(0.307)	(0.289)	(0.386)	(0.416)	(0.418)	(0.408)
Control variables												
Sp. proximate PV firms	-0.0266***	-0.0312***	-0.0272***	-0.0166**	-0.0160*	-0.0218**	-0.0154	-0.00597	-0.0495***	-0.0557***	-0.0517***	-0.0337***
	(0.00752)	(0.00739)	(0.00747)	(0.00683)	(0.00965)	(0.00964)	(0.00984)	(0.00958)	(0.0126)	(0.0128)	(0.0126)	(0.0118)
Sp. proximate universities	0.0344***	0.0386***	0.0372***	0.0275***	0.0203**	0.0232**	0.0203**	0.0103	0.0318***	0.0383***	0.0381***	0.0248**
	(0.00665)	(0.00664)	(0.00682)	(0.00708)	(0.00899)	(0.00936)	(0.00981)	(0.0112)	(0.0121)	(0.0122)	(0.0115)	(0.0115)
Governmental ties	-0.0774	-0.0430	-0.0470	-0.106	-0.0213	0.0363	0.0463	-0.0101	-0.0270	0.0543	0.0754	-0.0216
	(0.0791)	(0.0725)	(0.0715)	(0.0695)	(0.1000)	(0.0940)	(0.0935)	(0.0920)	(0.138)	(0.127)	(0.112)	(0.110)
Patent office	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Priority date	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Patent scope	0.0524***	0.0549***	0.0537***	0.0425***	0.0489***	0.0513***	0.0500***	0.0349***	0.0690***	0.0705***	0.0713***	0.0675***
	(0.00572)	(0.00578)	(0.00566)	(0.00632)	(0.00616)	(0.00589)	(0.00575)	(0.00653)	(0.00777)	(0.00791)	(0.00773)	(0.00691)
Constant	0.387	0.181	-0.0303	-0.358	-0.319	-0.631*	-0.856**	-1.204***	-0.471	-0.775	-0.896*	-1.319**
	(0.332)	(0.344)	(0.344)	(0.319)	(0.347)	(0.362)	(0.367)	(0.357)	(0.529)	(0.552)	(0.535)	(0.518)
Observations	1,259	1,259	1,259	1,259	1,259	1,259	1,259	1,259	1,259	1,259	1,259	1,259
Wald chi2	2,149.06	1,949.23	1,959.47	1,894.23	1,968.56	2,020.49	2,016.77	1,652.93	1,958.20	2,160.13	2,018.72	2,024.72
Prob>chi2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pseudo R2	0.2160	0.2147	0.1952	0.1078	0.2329	0.2193	0.2048	0.1637	0.3087	0.3115	0.2890	0.1772

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 22: Poisson Regression Models for Citation Windows of Infinite, 15, 10 and 5 Years

4.5 Discussion and Conclusion

4.5.1 Summary of Main Findings

The purpose of this paper is to identify patenting patterns as well as international and intersectoral knowledge flows for the German PV sector and to then deduct the key determinants of a firm`s PACAP, i.e., its ability to identify and assimilate external knowledge. I build my analysis on a dataset of 1,782 patent applications between 1976 and 2015, 8,573 cited patents, and 5,210 citing patents for a total of 148 firms. The main findings show a substantial growth in patent activity since the mid-1990s in conjunction with a higher level of female inventors, increasing industry-university R&D collaboration, and a high dependency of international (58.19% of cited patents between 1976-2015) and intersectoral (48.51%) knowledge flows for the German PV industry.

In a second step, I combine these insights with the antecedents of a firm`s PACAP described in the literature. I empirically examine inventor-individual, inter-organizational, and eco-systematic factors of a firm´s PACAP for three dimensions of external knowledge: general, international, and intersectoral. Starting with the inventor-individual factors, a general form of diversity reflected by the pure number of inventors and gender diversity have a significant positive effect on a firm`s PACAP along all three knowledge dimensions. Interestingly, cultural diversity has a positive sign for all three dimensions but is only significant with respect to foreign knowledge flows. This underlines the importance of cultural and linguistic factors for accessing global knowledge flows. A higher educational level among the inventors has no significant influence on PACAP, which might be due to limited documented educational information in a patent.

Turning to inter-organizational factors, a higher number of applicant firms decrease and a higher cultural diversity among the applicant firms increases the ability to absorb external knowledge. An increase in PACAP through cultural applicant diversity is in line with my argumentation; however, the counterintuitive observation that a higher number of firms decrease PACAP requires cautious explanation. First, the rationale of multiple applicant firms per R&D project might refer to risk-sharing, enhanced financing opportunities, economies of scale, and the leverage of existing internal knowledge rather than an intensified search for and acquisition of external knowledge. Second, higher costs for monitoring, communication, coordination, and trust-building (Ferreras-Méndez et al., 2016) as well as limited managerial attention (Ghisetti et al., 2015; Kim et al., 2016) restrict the search intensity. Third, strategic motives behind patenting and a presumed greater reputation of joint R&D programs in the eyes of patent examiners might reduce the incentive to add relevant prior art and affect the analysis negatively. This heterogeneous picture of industrial co-patenting requires further research work, while my results undoubtedly imply that industry-university R&D collaboration increases a firm`s PACAP as it offers complementary academic knowledge of basic research.

The control variables for eco-systematic factors emphasize the positive industry-university R&D linkage. A higher number of spatially proximate universities and research institutes increase a firm`s PACAP along all three knowledge dimensions, which highlights the existence of local knowledge spillovers. In contrast to my arguments, the existence of further PV firms within an ecosystem has a significant negative effect on a firm`s PACAP. This counterintuitive result can be explained by cognitive lock-ins and a predominance of redundant information (Crescenzi et al., 2016; Jansen et al., 2005), insufficient investments in internal R&D and learning capabilities

(Camisón and Forés, 2011; Lee, 2009), a decreased importance of geographic proximity due to advanced communication or even its substitution by organizational, social, cultural-ethnic, and cognitive-technological proximity (Crescenzi et al., 2016; de Jong and Freel, 2010) as well as strategic motives to disclose information rather than co-invent. I encourage future work on this topic to account for a firm`s network position (Fang et al., 2017). Finally, the relationship with governments has no significant influence on a firm`s PACAP and does not offer access to additional external knowledge. Part of the explanation for this might be the operationalization via public R&D funding data instead of publicly announced knowledge exchange formats or documented personal contacts.

My paper makes three main contributions to ACAP theory (Cohen and Levinthal, 1989, 1990; Zahra and George, 2002). First, the holistic view of inventor-individual, inter-organizational, and eco-systematic factors brings together unlinked antecedents of a firm`s PACAP described in previous studies. Second, this paper is one of the few studies apart from Schmidt (2005) to control for different types of external knowledge, thereby accounting for the multi-dimensionality of knowledge flows. Third, my patent-based methodology complements previous survey-based analyses (e.g., Araújo Burcharth et al., 2015; Camisón and Forés, 2011; Ferreras-Méndez et al., 2016) or case study designs (Sjödin and Frishammar, 2015). In addition, the empirical application to the German PV sector further develops the scientific discussion on ETIS regarding one of its core research gaps, namely knowledge acquisition and knowledge flows (Gallagher et al. 2012). My paper undermines the existence of international and intersectoral knowledge flows, explores the role of different knowledge sources within innovation systems such as universities, governments, or firm networks, and emphasizes the importance of a firm`s PACAP for benefiting from knowledge spillover.

4.5.2 Policy and Managerial Implications

The results are highly relevant for both managers and policy makers. They show managers how their operations depend on international and intersectoral knowledge flows to generate new inventions and sensitizes them to knowledge drains. Both insights allow them to identify technological and commercial partners as well as competitors. Second, I encourage innovation managers to take cultural and gender diversity into account when selecting staff for inventor teams as they increase a firm`s PACAP, especially in the case of foreign knowledge. Third, my results suggest that it is important to enhance international and industry-university R&D collaboration as they are an effective vehicle for additional external, foreign, and non-PV-sectoral knowledge. In contrast, a higher number of applicants per se do not lead to an increased PACAP and the trade-off between shared project risks and combined R&D resources versus higher transaction costs and the lack of managerial attention has to be considered. Fourth, universities are an important factor for location considerations due to local spillovers of complementary knowledge, while a higher number of spatially proximate PV firms reduce PACAP.

This paper highlights four main implications for policy makers. First, a nation`s key initiative has to be public programs for fostering gender and cultural diversity as they enable firms to increase their PACAP and thereby contribute to a nation`s innovativeness and welfare. Public owned companies should hereby serve as role models for the private sector and actively train women and culturally diverse employees. In addition, governments should educate society on diversity. Second, this paper highlights the important role of universities and research institutes for the private sector by showing positive effects on a private firm`s PACAP through formal industry-university collaboration and local knowledge spillovers. I therefore suggest that future public R&D funding be invested in academic co-inventing projects and encourage the public scientific community to intensify its links with the private sector. Third, my results contradict regional cluster building initiatives and support international R&D collaboration. Policy-makers should therefore stimulate global collaboration, e.g., via investments in communication infrastructure, open trade and research agreements, or promotion of employee mobility. Fourth, governmental ties measured through public R&D funding have no significant effect on a firm`s PACAP. This finding should encourage public R&D funding agencies to intensify their role as knowledge providers and as connectors of multiple R&D actors to exchange knowledge.

4.5.3 Limitations and Suggestions for Future Research

Although patent citation analysis enables access to a rich and objective set of data, I view my methodology as a complementary yet limited research approach to the dominating survey-based studies within the field of ACAP research. The first limitation implies that patent citation data measure a firm`s PACAP only with respect to other patents, i.e., already codified knowledge and neglect tacit knowledge. Furthermore, patent data are an imperfect indicator of R&D collaboration and require additional firm-internal knowledge (Bergek, Bruzelius 2010). Surveys of CEOs and innovation managers can overcome these restrictions by asking questions on, e.g., individual employee's educational and cultural background, their job roles and prior working experience; a firm`s internal R&D structures and budgets; or its network of knowledge partners.

The second limitation refers to the initial assumption that citation data are an appropriate indicator of a PV firm`s PACAP of external knowledge critical to their existing PV operations and technology. I am, however, aware that there is no conclusive definition of either a "single PV operation or technology" or what I call "a PV firm." I reduce this bias by using tailored patent search strings, the geographic restriction to Germany, careful selection of firms, and by limiting the observation period to 2006–2015. However, I suggest an even more granular approach to control for certain sub-technologies of the PV sector as well as the exact position of a firm within the PV value chain and whether it also operates outside the PV sector. Sophisticated networking analysis enables a pairwise comparison of knowledge flows controlling for geographic, social, cultural, organizational, and technological proximity.

Third, the unit of analysis is the German PV sector, a leading country for PV technology. I suggest broadening the scientific lens to other leading countries (USA, Japan, or China) and developing countries. In this global context, other sources of knowledge exchange, e.g., trade, development of foreign subsidies and employee mobility, would deepen the understanding of knowledge flows to further promote the development of renewable energies.

5. Conclusion

In this dissertation, I address two distinctive research questions originating from the scientific literature on ETIS (Gallagher et al. 2006; Gallagher et al. 2012; Grübler et al. 2012), and also provide interesting findings for the overarching literature stream of IS (Freeman 1987; Lundvall 1988, 1992; Nelson 1984, 1988, 1993). The first research question discusses the impact of innovation policy on firm-level innovativeness and the second one analyses knowledge and learning within the ETIS. **Papers 1** and **2** contribute to the first question and **Paper 3** to the second one. The co-authored **Paper 1** (with Dr. Claudia Doblinger) has been published in the journal Energy Policy. It indicates that institutional influences in terms of public R&D funding on a firm`s innovative performance are ambiguous as they increase patent quantity, but have no significant influence on patent quality. The results presented in **Paper 2** give guidance how formal institutions (e.g. energy laws and regulations) affect an incumbent energy utilities’ business model. I find certain evidence that a substantial part of a firm`s scope, direction, degree, and frequency to innovate its business model corresponds to the frequency, predictability, velocity, and radicalness of legal environmental dynamics. In **Paper 3**, I contribute to the second research question on knowledge and learning by examining the diffusion of codified knowledge within the ETIS on an international and intersectoral level. In addition, I elaborate on what kind of inventor-related, inter-organizational, and other systemic determinants firms should develop to incorporate these knowledge flows in order to improve their innovativeness. For each paper, I apply the ETIS as the theoretical framework and combine it with further suitable theories, i.e., the resource-based view in **Paper 1** (Wernerfelt 1984; Barney 1986, 1991; Dierickx, Cool 1989), the contingency framework on business model dynamics in **Paper 2** (Saebi 2015), and the absorptive capacity theory in **Paper 3** (Cohen, Levinthal 1989, 1990; Zahra, George 2002; Lane et al. 2006). In the following sections, I summarize the main findings (5.1), theoretical contributions (5.2), practical implications (5.3), and limitations (5.4) of all three papers and also highlight the specific insights of each paper.

5.1 Summary of Main Findings

In **Paper 1**, we draw on the RBV (Wernerfelt 1984; Barney 1986, 1991; Dierickx, Cool 1989) in order to examine how the institutional influence of public R&D as a financial resource affects a renewable energy firm`s innovation performance. The database consists of 1,448 German PV and wind firms and 206 public granted R&D projects with a volume of 235 Mio € between 2006 and 2015. The empirical results indicate a heterogeneous picture of the rationale for public R&D policies to balance private underinvestment into R&D (Nelson 1959; Arrow 1962). On the one hand, public R&D funding, in terms of absolute monetary value and the frequency of past funded R&D projects, increases the number of applied patents. On the other hand, it does not lead to technological breakthroughs, as directed by the insignificant effect on the number of patent citations. Further key findings provide support that a firm`s overall financial situation increases the patent quantity, but has no significant impact on patent quality. Turning to the intangible resource of a firm`s technological knowledge base, we find certain evidence for a positive impact on both patent quantity and quality. Physical resources (estimated by the value of total assets), age, and location have no significant effect on a firm´s innovation performance. The holistic analysis of various firm resources meets the demand of Galbreath (2005) for research in the RBV context. In addition, we suggest innovation managers to incorporate public R&D funding as an R&D financing vehicle and to constantly invest in a firm`s knowledge base. A second group of actors who benefit from the findings are governmental bodies. We propose they re-evaluate the long-term implications of funded R&D projects, dedicate more money to risky R&D projects with a higher technological relevance, and include a firm`s knowledge base (indicated by its patent stock, R&D budget, and employees) as well as subordinate a firm`s size and age as funding selection criteria. The findings are important for an efficient usage of public money and the development of energy technologies, which still depends on a substantial receives a fundamental amount of public R&D funding.

In **Paper 2,** I analyze how laws and regulations influence an energy incumbent`s business model innovation within the observation period 2009–2017. The French energy incumbent EDF, in a relatively stable legal environment, extends its value proposition of low carbon electricity provision only incrementally through digital energy services and adjusts its customer interfaces correspondingly. As it maintains its power generation fleet with a focus on nuclear and hydro and keeps its financial investments constant, its overall business model changes of incremental, gradual, narrow, and natural adjustment tends to correspond to the theoretical expectations of Saebi (2015). Similar observations can be found for British SSE, which under a more dynamic legal environment incrementally changes all business model elements. Balanced investments in a broader value proposition, greener infrastructure, and a digital, service-orientated customer interface tend to confirm the assumed strategic behavior of business model alignment. In light of fundamental environmental dynamics due to the prompt nuclear phase-out in Germany, German E.ON separates its business model into two distinctive units. While the one unit maintains conventional power generation and energy trading (Uniper), E.ON itself focuses on renewable energies, customer solutions, and networks, and executes the nuclear segment as a non-core activity. All business model elements undergo radical changes, which is in line with the expected business model innovation archetype. Business model changes observable at all three sample firms include servitization, digital customer interfaces, and the growing importance of renewable energies and regulated businesses. These insights not only demonstrate potential support for Saebi's (2015) theoretical framework on business model dynamics for the electricity sector, but also address the core research need of ETIS on the interaction of institutions and actors. It differs from previous studies in that it applies a dynamic, cross-country analysis with a focus on post-Fukushima implications for energy incumbents.

In **Paper 3**, I visualize patenting patterns and the relevance of international and intersectoral knowledge flows for the German PV sector based on patent-citation analysis. Interesting findings include an increase in female inventors, larger inventor teams, and a higher level of industry-university R&D collaboration since the mid-1990s. Furthermore, 58.19% of the patents cited by German PV firms between 1976 and 2015 originate from foreign firms, and 49.21% of the cited patents are granted by firms outside the PV sector. In a second step, I apply absorptive capacity theory (Cohen, Levinthal 1989, 1990; Zahra, George 2002; Lane et al. 2006) to a sample of 1,446 patent applications and 7,867 cited patents for 129 German PV firms between 2006 and 2015. The empirical findings show a significant positive relationship between inventor diversity (gender, culturally, in general), international as well as industry-university R&D collaboration on a firm`s PACAP, i.e., a firm`s ability to acquire and assimilate external knowledge. Spatial proximity of innovating PV firms to universities also contributes positively to a firm`s PACAP while spatial proximity to other PV firms has a negative and governmental ties no significant influence. A counterintuitive result is the negative effect of intensified intra-industry R&D collaboration on a firm`s PACAP. I see two potential reasons why a firm`s PACAP decreases with a higher number of co-inventing firms: the use of R&D synergies as well as higher monitoring and transaction costs (Ferreras-Méndez et al. 2016) limits the resources and time spent searching for external knowledge. In this paper, I emphasize the conceptual advantages of the ETIS as it differentiates the examined knowledge flows into general, international, and intersectoral flows and thus overcomes the limitations of an NIS and SIS perspective. The systemic perspective of ETIS allows for a holistic view of a firm`s PACAP theory, which enables to connect previous unlinked antecedents of inventor-individual, inter-organizational, and eco-systemic factors. The paper differs from previous studies on PACAP theory in that it uses the more granular and objective patent-citation analysis approach instead of a survey-based analysis.

In **Papers 1** and **2**, I contribute to Research Question 1 by examining institutional influences on firm innovation performance. In **Paper 1**, I focus on financial stimuli on firm-level process and product innovation. In **Paper 2**, I concentrate on how laws and regulations affect the scope, direction, degree, and frequency of business model innovation. In **Paper 3**, in contrast, I answer Research Question 2 on knowledge and learning by illustrating patenting patterns as well as international and intersectoral knowledge flows relevant to energy technologies. I also determine key success factors for firms to increase their absorptive capacity and benefit from interactive learning inside the ETIS. I not only answer the two overarching research questions, but also contribute to the further theoretical development of the ETIS (5.2.1) and deepen the understanding of the three established theories through its application to the energy sector (5.2.2).

5.2 Contributions to Theory

5.2.1 Contribution to ETIS

As discussed in Section 1.1.4, I focus the research on ETIS on (a) the role of actors and institutions (b) knowledge and learning as well as (c) methodological shortcomings and data needs. For (a) the role of actors and institutions, I find support that actors and institutions are closely linked within an innovation system. I find evidence that firm behavior can be steered by institutions directly in the form of public R&D funding **(Paper 1)** as well as laws and regulations **(Paper 2),** but also indirectly through common beliefs and traditions **(Paper 3)**. However, I also demonstrate throughout all three papers that institutional influences do not rule out an individual firm`s strategic choices and innovation performance. Second, in **Paper 1,** I find support for the positive effect of supply-push policies on the diffusion of renewable energy technologies as funded firms apply significantly more patents than their peers do; however, my findings also indicate that these funded R&D projects do not lead to technological breakthroughs measured by the average number of patent citations. This shows potential for a more effective use of public R&D funding as private firms seem to invest public R&D funding for projects they would have run anyway instead of for ground-breaking and risky R&D projects. Third, in **Paper 2,** I gain evidence that different institutional settings lead to different firm behavior. The case studies of energy markets in France and UK emphasize the institutional function to decrease uncertainty and communicate transparently in order to allow firms a long-term orientated strategic management and an appropriate transition of their business models. In contrast, the case study for the German energy market indicates that sharp and fundamental institutional changes lead to major reactions from incumbent firms, including organizational splits and job losses. Fourth, in **Paper 3,** I find that institutions in terms of common beliefs, traditions, and perceptions affect a firm`s absorptive capacity. The positive effect of gender diversity should encourage our society and educational system to overcome traditional role models and actively support women in technological fields. The positive result for industry-university R&D collaboration indicates that traditional barriers between pure scientific and profit-orientated actors have to be overcome to serve the higher social goal of renewable energy diffusion. I also find evidence that the interaction with other actors (firms, research institutes and universities) within the ETIS affects a firm`s innovativeness.

With respect to (b) knowledge and learning, I address (in **Paper 3)** the research request of the ETIS to document and analyze historical data on knowledge spillovers between various technological fields and countries (Gallagher et al. 2012) with a patent-citation analysis running since 1976. Furthermore, I gain empirical evidence that diverse inventor teams absorb more external knowledge, thus providing new recommendations for intra-firm knowledge and learning capability building. I also provide a better understanding of extra-firm knowledge creation and learning processes, as I empirically demonstrate a positive relationship between international and industry-university R&D collaboration and a firm`s potential absorptive capacity. In addition, I find indications for a negative relationship between excessive intra-industrial co-patenting activities and potential absorptive capacity. Finally, I observe that knowledge spillovers through spatial proximity to universities exist while spatial proximity to other PV firms seems to limit the exchange of knowledge.

Regarding (c) methodological shortcomings and data needs, I create a rich set of publicly accessible and reliable information on firm-level innovation input and output data, knowledge spillovers as well as institutional influences. In combination with the application of patent and citation data analysis (**Papers 1** and **3**) as well as the Business Model Canvas (**Paper 2**), I thus satisfy the research need for internationally comparable and comprehensible research designs. I hereby provide other scholars guidance on a systemic measurement of innovation and the operationalization of knowledge flows. Within all three papers, my focus is to not only to describe the interactions of actors and institutions within the ETIS but to also elaborate their causal relations by hypotheses testing and case-study comparison. It is also my intention to transfer the ETIS from a static to a more dynamic framework, as I analyze the interaction of firm-level innovation and institutional influences in all three papers along extended time horizons instead of points in times. This dynamic aspiration enables historical comparisons, e.g., for **Paper 2**, I discuss business model changes for three incumbents over almost a decade, while for **Paper 3,** I gain insights into evolving patenting patterns, female participation in R&D, industry-university R&D collaboration as well as international and intersectoral knowledge flows since 1976 for the German PV sector.

5.2.2 Contribution to Paper Specific Theoretical Foundations

Through this dissertation, I not only contribute to the ETIS, but also to the applied theories of each paper. My co-author, Dr. Claudia Doblinger, and I base **Paper 1** on the RBV (Wernerfelt 1984; Barney 1986, 1991; Dierickx, Cool 1989) and explain heterogeneous firm R&D performances through differences in a firm`s resource base. Our approach thereby differs from the “classic” RBV, which links a firm`s resources to its competitive advantage. In addition, we enrich the scientific debate on which financial resources affect a firm`s innovative performance positively as we don`t apply traditional R&D financing sources such as bank loans or venture capital but focus on public R&D funding (Hall, Lerner 2010). We meet the requirements of Galbreath (2005) to analyze a bundle of resources simultaneously as we include an intangible resource (a firm`s knowledge base), physical resources, and further indicators for financial resources (past funding intensity, firm`s overall financial situation). In **Paper 2,** I contribute to the further development of the contingency framework on business model dynamics (Saebi 2015). The specific application on the energy sector is, in my opinion, of high scientific and practical relevance as the energy sector clearly differs from other sectors. An energy incumbent`s value proposition is based on electricity provision and is thus hardly differentiable from end-customers. Its infrastructure consists of power plants with an operational lifetime of over 50 years, which are thus not easily exchangeable. In addition, the infrastructure is currently shifting from centralized, uni-directional electricity generation to a decentralized and digitalized energy infrastructure, which requires additional investments and capabilities from energy incumbents. Customers' interfaces have been passive over decades and are now transforming into a high level of service, digital channels, and prosumers. Finally, the business model element financials is confined to regulated and de-regulated business. Given these characteristics, theory development is a main contribution, as to my best knowledge, the universal framework of Saebi (2015) has not yet been applied to the energy sector. In addition, my results indicate that environmental dynamics should cover legal, competitive, technological, and social aspects as not all business model trends can be explained with legal environmental dynamics. Finally, the combination with the business model CANVAS (Osterwalder 2004; Osterwalder, Pigneur 2011) and the developed indicators per business model element facilitate future research for further theory building. In **Paper 3,** I further develop the absorptive capacity theory (Cohen, Levinthal 1989, 1990; Zahra, George 2002; Lane et al. 2006) as I first distinguish between various concepts of ACAP and then apply a stringent empirical approach to define the determinants of a firm`s PACAP for codified knowledge in terms of patent data. In contrast to previous studies on ACAP theory, I derive a holistic set of hypotheses on inventor diversity, inter-organizational R&D

collaboration, and the influence of surrounding actors of the same innovation system (other PV firms, universities, governmental bodies) rather than examine a singular antecedent of a firm`s ACAP. A second difference from previous studies is that I control for the multidimensionality of knowledge and distinguish between international, intersectoral, and general external knowledge flows. Unlike previous survey-based studies, I use patent and citation data to track knowledge flows and thus gain additional empirical legitimacy for the absorptive capacity theory.

5.3 Practical Implications

5.3.1 Implications for Policy Makers

In this dissertation, I examine the interdependencies of innovation policies and firm behavior in the transforming and highly institutionalized energy sector. A first basic observation for policy makers is the fact that public policy enables and constrains firm behavior as well as a firm`s dynamic and scope to innovate. Second, I find evidence for the international and intersectoral dependencies for energy technologies and provide a practical analysis framework for policy makers in the form of the ETIS. I realize that each politician is legally bound to pursue a nation`s interests. In the case of the energy sector, this includes providing energy security at affordable prices for domestic industry and private households, creating jobs in the domestic market, providing subsidies for domestic firms and research institutes as well as reaching national climate targets, which in summary urge the application of an NIS perspective. With this dissertation, however, I provide empirical evidence and practical guidelines for favoring an ETIS view over the NIS for future energy policies. The draining of knowledge from German PV firms to Chinese competitors and thus the loss of thousands of jobs and the waste of millions of subsidies is anecdotal evidence in favor of the ETIS. In **Paper 1**, I find support that policy makers can foster innovation at a firm-level as publicly funded renewable energy firms apply significantly more patents than their non-funded peers. However, this positive institutional effect only holds true for patent quantity but not quality. Policy makers could probably allocate public money more efficiently through a stronger weighting of an R&D project`s technological relevance and a firm`s existing knowledge base during the application process, a re-evaluation of R&D projects after several years as well as bonus payments. In **Paper 2**, I focus on an institution's function of reducing uncertainty, managing conflicts and cooperation, and providing incentives for innovation (Edquist, Johnson 1997). The comparison of three different energy markets and their formal institutions (laws and regulations) allows first indications that legal environmental dynamics allow energy incumbent firms to gradually adjust their existing business models or force them to fundamentally innovate them. In **Paper 3**, I demonstrate how innovation policy can both foster and hamper knowledge and learning processes on a firm level. The promotion of gender diversity and the encouragement of women to take up technological careers, the establishment and an adequate funding of universities and research institutes, the call for more industry-university R&D collaboration as well as the support for international R&D collaboration and employee mobility tend to increase a firm`s potential absorptive capacity and subsequently lead to more innovation in energy technologies. In contrast, I observe that regional cluster building initiatives and public R&D funding do not stimulate a firm`s potential absorptive capacity.

A conclusive look at all three papers emphasizes the challenge for politicians to address the needs of all actors within an ETIS adequately. I encourage politicians to aim for a greener energy future through reliable and transparent incentives for innovation, technology openness and competition, support of industry-academic research activities, investments in the educational system, and clear communication to the public.

5.3.2 Implications for Managers

Besides political implications, my findings provide possible options for managers, who steer their firms in an institutionalized sector with a variety of actors jointly developing new technologies. As an initial and basic insight, I point out on three consciously selected dimensions that each firm as an actor is part of a larger innovation system: In **Paper 1,** I analyze the financial aspect of institutional influence via public R&D funding on firm-level innovativeness. The findings should encourage innovation managers to use public R&D as an effective financing source for R&D projects and indicate its positive long-term effect on firm innovativeness. In **Paper 2**, I focus on the institutional influence through laws and regulations. I find support that institutions can force managers to innovate existing business models. A potential practical implication for innovation managers is to actively work on close governmental ties as well as to stimulate and anticipate upcoming regulative changes. In **Paper 3**, I discuss the importance of other actors regarding knowledge acquisition. The illustration of knowledge flows through patent-citation analysis illustrates the high degree of international and intersectoral knowledge exchange for energy technologies. Furthermore, a possible recommendation for innovation managers is to foster industry-university R&D collaboration and reconsider inter-industrial cooperation on a national level. I also suggest thereby cautiously that innovation managers should consider various channels of knowledge exchange, i.e. formal channels (in terms of R&D collaboration) but also informal ones (caused by spatial proximity).

In addition to these recommendations on how to react to and leverage external influences of other actors and institutions, I established a set of suggestions for firm-internal purposes. In **Paper 1,** I highlight the importance of permanently investing in the employees and equipment in an R&D

department in order to build up a solid firm internal knowledge base as this improves a firm`s innovativeness, as indicated by a higher patent quantity and quality. Based on the empirical results, I find support to encourage firms to apply for public R&D funding. The benefits of public R&D funding for a firm`s innovativeness outweigh the required efforts for the grant application and documentation as well as the disclosure of project results. In **Paper 2**, I find evidence that firms should adopt their business models to the legal environmental dynamics. This adoption would have implications on the corporate culture and innovation processes. The first gathered insights that business models of energy utilities tend towards servitization, customer proximity, and digital channels also affect employee development and recruitment processes. Future employees probably need a higher social and digital competence. The results also indicate to a certain degree the importance of close governmental relationships. In **Paper 3**, I find first support to staff gender and culturally diverse inventor teams as they identify and acquire a higher level of external knowledge. The results also indicate the benefits of international and industry-university R&D collaboration for confronting the internal R&D department with new perspectives and working modes, and giving them access to new complementary knowledge.

Although this dissertation implies insightful implications for both politicians and managers, it includes limitations and a need for future research, which I outline in the next section.

5.4 Limitations and Future Research

I structure the limitations and future research along different aspects of my dissertation, namely the further development of the *ETIS* with a focus on *Western Europe (especially Germany),* the *cumulative nature* of my dissertation as well as its *innovation management research perspective*.

First, as mentioned in the introduction, the two research questions are not limited to the *ETIS* but can also be applied to the NIS, RIS, SIS, and TIS in order to generalize the findings. As an example, the hypothesis in Paper 1 on the effectiveness of public R&D funding can be extended to all technologies within a given nation (region) and be compared with a national (regional) innovation outcome (e.g., patents) or other economic indicators (e.g., growth rates of gross domestic products, employment rate). In the same way, the combination of various innovation systems is an interesting research area. Given the decentralized nature of future energy grids with different regional regulations, funding schemes, local natural conditions, and public opinions, the ETIS combined with the RIS can explain why different energy technologies diffuse successfully in certain areas but fail in others. Second, the geographic focus on *Western Europe and especially Germany* refers to the high level of institutional influences within these countries, the technological and scientific leadership in (renewable) energy technologies, and a resilient amount of historical data. However, in order to meet international climate goals and improve the global energy security, future research has to adapt the findings to developing countries. Third, the *cumulative structure* of the dissertation forces me to condense the research methodologies of each paper. However, I acknowledge, that a mixed-methods-approach would be worthwhile to legitimize the results. Fourth, I encourage future research teams to extend my *innovation management research perspective* and to undertake interdisciplinary research in order to fully leverage the knowledge of engineering and business administration disciplines. An inspiring study in this context is, for example, Huenteler et al. (2016).

In **Paper 1,** I address the research call from (Galbreath 2005) to examine multiple firm resources simultaneously within the context of RBV. However, an extension of the analysis with additional firm resources (e.g., equipment in R&D laboratories, internal R&D budgets, employee`s knowledge and qualifications, organizational R&D structure) enables a deeper understanding of how governments could tailor public R&D funding schemes more efficiently within an innovation system. With **Paper 2,** I satisfy the research need for a dynamic and cross-country analysis (Engelken et al. 2016; Kern, Markard 2016), but focus the case-study on energy laws and regulations, as this has not been discussed in detail in previous studies. Future research could broaden the scope of the environmental dynamic and cover changes in competition, public opinion, and technological progress. In **Paper 3,** I contribute to the absorptive capacity theory and ETIS for codified knowledge in the form of patent and citation data, but do not account for tacit knowledge. A future survey-based approach can overcome this shortcoming. Finally, a fundamental part of this dissertation (**Papers 1** and **Paper 3**) applies patent and citation analysis, the advantages and limitations of which are worthy of more detailed discussion. Fundamental critics of patent analysis argue that “not all inventions are patentable, not all inventions are patented, and the inventions that are patented differ greatly in “quality” […] ” (Griliches 1990, p.1669). However, (Dernis, Guellec 2002) argue that only very few examples of economically significant inventions have not been patented. A further limitation of this approach is that patents mainly measure invention instead of innovation as they do not measure the economic success of an invention. Methods for accounting for the commercialization of an invention would include directly linked sales data, surveys amongst patent holders, renewal rate of patents and their license fees. Besides this terminological distinction, different national patent office laws, policies, and resources affect the quantity of granted patents and citations (Griliches 1990) and thus the quality of corresponding research results. Furthermore, empirical studies show that patent data do not fully reflect a firm`s R&D collaborations (Bergek, Bruzelius 2010) nor are inventors completely aware of added citations (Jaffe et al. 2000). Studies on strategic patenting argue that strategic motives such as an increased reputation, licensing incomes, better negotiation position, or its use for internal R&D evaluation are more important than the traditional argument of protecting a firm`s invention from imitation (Blind et al. 2006). These strategic motives negatively influence patent analysis to measure a firm`s innovativeness or knowledge flows. Finally, the inclusion of irrelevant patents and the exclusion of relevant patents is a source of errors. However, detailed patent search strings built on patent classification and relevant keywords reduce those errors (Popp 2005; Johnstone et al. 2010). In contrast to the limitations, patent analysis provides multiple advantages. It provides a granular level of information about the invention (content description, degree of novelty, patent classification, time), the involved applicants (individual/firm, count, home country) as well as the number of forward and backward citations. Secondly, patent data are publicly accessible and available for various countries over a long period of time (Dernis, Guellec 2002; Hall et al. 2001; Dernis, Guellec 2002). Thirdly, patent data as an output factor exceeds input factors such as R&D expenditures or R&D personnel in order to determine firm innovativeness, as they reflect the result of the R&D process (Jaumotte, Pain 2005; Johnstone et al. 2010). In summary, I share the view that patent analysis is an insightful measurement criterion for invention output and a valuable indicator of firm-level innovation performance. This optimistic view is in line with traditionally established innovation research (Schmookler 1966; Scherer 1982; Griliches 1990) and its increasing application to energy technologies (Johnstone et al. 2010; Nemet 2012; Bointner 2014; Duch-Brown, Costa-Campi 2015; Battke et al. 2016; Guan, Liu 2016).

5.5 Concluding Remarks

Within my dissertation, I contribute to the ETIS as I add new theoretical and practical insights concerning (a) the role of actors and institutions, (b) knowledge and learning and (c) methodology shortcomings and data. With respect to (a), I link the ETIS with the RBV **(Paper 1)** to show the institutional influence of supply-push policies on firm-level innovativeness. Furthermore, I combine the ETIS with the contingency framework on business model dynamics **(Paper 2)** to illustrate how institutions in terms of laws and regulations determine the scope, direction, degree, and frequency of incumbent energy utilities' business model innovation in the different institutional settings of France, the UK, and Germany. Regarding (b), I apply the absorptive capacity theory and determine the antecedents of a firm`s knowledge absorptive capacity **(Paper 3)**. With respect to (c), an intense data collection effort on public R&D funding, patent application and citation data as well as institutional information resulted in comprehensible, internationally adoptable and dynamic research designs with a firm-level perspective. In summary, the generated theoretical contributions and empirical evidences will promote the expansion of the still young research field of ETIS. My personal aim with this dissertation, however, is not only a further theoretical development of the ETIS as a sub-stream of the IS perspective, but to also provide a list of practical and political implications to foster the global energy transition. I encourage innovation managers, politicians, and society to understand energy transformation as an inevitable process within a common innovation system of various actors and institutions. Although, the various actors follow different motives within this system, we will either jointly solve the climate challenge for ourselves and, above all, for future generations or we will jointly fail.

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