The role of deployment policies in fostering innovation for clean energy technologies
insights from the solar photovoltaic industry

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The Role of Deployment Policies
in Fostering Innovation for Clean Energy Technologies –
Insights from the Solar Photovoltaic Industry

A dissertation submitted to
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for the degree of
Doctor of Sciences

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2013
“Problems cannot be solved at the same level of awareness that created them.”

Albert Einstein
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I personally consider this section to be the most important part of my dissertation – not only because it probably is the only part that many will ever read but also because it gives me the opportunity to express my heartfelt gratitude to all those people without whom this dissertation would not exist, or would at least look completely different. I am deeply thankful for the support I have received throughout the last three years in so many ways and am certainly a different person than when I started the endeavor of my PhD.

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Abstract

A question of major importance is how policy makers can foster technological progress in clean energy technologies, so as to alleviate adverse environmental impacts of the energy sector, reduce the dependence on fossil fuels and create new jobs in dynamic high-tech industries. Whereas until the end of the 1980s government support largely focused on the direct funding of research and development (R&D), during the last twenty years there has been an increasing focus on so-called deployment policies, targeted at increasing the diffusion of clean energy technologies. Deployment incentives, such as feed-in tariffs, have been very effective in bringing technologies to the market. Yet, many clean energy technologies are still far from being cost competitive with fossil-fuel based energy sources. Therefore, this dissertation addresses the question how deployment policies affect technological innovation beyond a diffusion of existing technologies.

To examine the link between deployment policies and technological innovation, this thesis combines and builds upon insights from the disciplines of economics, organizational theory and innovation studies. Specifically, it contains four papers, each of which addresses a particular gap in the extant literature. The first paper scrutinizes the detailed mechanisms through which deployment policies affect technological learning at the firm level. The second paper investigates the role of knowledge spillovers as an important moderator between policy-induced innovation and the economic competitiveness of the innovating firms. The third paper addresses the question to which extent the design of deployment policies is endogenous to the technological change they seek to foster. Finally, the fourth paper studies the effect of policy-induced innovation on the economic viability of technologies complementary to those directly benefiting from market support.

All four papers draw on empirical data from the solar photovoltaic (PV) industry. PV offers major technological potential for clean electricity generation. However, due to the high costs of the technology, the PV industry is still strongly dependent on deployment policies, making it an ideal case to study their effects and dynamics. In line with the different phenomena to be investigated, this dissertation applies a mix of both qualitative and quantitative methods, including comparative and longitudinal case study research, panel data regression analysis and techno-economic modeling.

This dissertation makes four major contributions to the extant literature. First, it is shown that deployment policies are powerful means to spur firm-level technological learning but that firms pursuing less mature technologies are not able to benefit from deployment policies to the same extent as those with more mature products. As a result, strong policy-induced market growth raises the risk of a technological lock-in into more mature technologies. Second, empirical evidence is presented which demonstrates that firm-level innovation in PV technologies is driven by knowledge
spillovers from other firms. Importantly, these spillovers are facilitated by investments in both R&D and manufacturing equipment, which has implications for the literature streams on environmental innovation and absorptive capacity. Third, deployment policies are shown to be endogenous to the technological change they induce. Unforeseen dynamics of policy-induced technological change require policy makers to adjust the design of policies, leading to a cycle of issues and solutions labeled ‘compulsive policy-making’. Fourth, innovation induced by deployment policies affects the economic viability of complementary technologies. This suggests that studying the effect of deployment policies requires a perspective that considers their influence on the broader technological system, rather than individual technologies.

These insights allow deriving several recommendations for policy makers and corporate managers. Policy makers should design deployment policies in a way that reduces the risk of a technological lock-in, e.g., by complementing them with supply-side incentives. It is of critical importance that deployment policies can be flexibly adapted to unforeseen developments in the technological sphere. Moreover, if intended as industry policy, policy makers should foster deployment in a way that reduces knowledge spillovers to foreign firms, e.g., by focusing support on industries that more strongly rely on tacit knowledge. Corporate managers of firms that operate in industries affected by deployment policies should closely monitor policy dynamics and drivers as these policies have the potential to significantly disrupt established industry structures. A major task of managers in the face of policy-induced market growth is to find an adequate balance between leveraging existing technologies to exploit arising revenue streams and exploring promising future technologies. In this process, firms need to anticipate and strategically manage knowledge spillovers to secure longer-term competitiveness.
Zusammenfassung


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1 Introduction

1.1 The Challenge: Reconciling the Rising Demand for Energy with the Protection of Natural Ecosystems

Ensuring the supply of the world with clean and reliable energy is one of the major challenges of our time. Energy is required to meet basic human needs, such as lighting or cooking, and builds the basis for growth in social and economic welfare. Between 1973 and 2010 global primary energy demand per year has risen by 85% from 196 EJ to 363 EJ (IEA, 2012b). Much of this growth was driven by global population growth which increased by 74% from around 3.9 BN to 6.9 BN (U.S. Department of Commerce, 2013). At the same time, however, mainly due to rising living standards in developing countries, also average energy consumption per capita rose by 6.7%.

While energy remains the lifeblood of modern societies, the world’s increasing hunger for energy comes at a cost. Since fossil fuels, such as coal and gas, still account for approximately 81% of all energy sources (IEA, 2012c), increases in energy demand have been closely connected to a rise in global anthropogenic greenhouse gases (GHG). For example, in 2004 the combustion of fossil fuels was responsible for around 57% of all anthropogenic GHG emissions (Rogner et al., 2007), making the energy sector the largest contributor to global climate change and its potentially severe consequences for mankind (IPCC, 2007). Moreover, accidents like the BP “Deepwater Horizon” oil spill in 2010 and debates about groundwater contamination through hydraulic fracturing demonstrate that the extraction of fossil fuels bears the risk of significantly disrupting natural ecosystems (Kerr et al., 2010).

Together, the growing demand for energy and the inherent problems associated with fossil fuels call for a major change in the way in which we produce and use energy. In the 2010 Cancun Agreement the international community agreed that, to prevent the most serious damages, temperature rises from anthropogenic GHG emissions need to be limited to 2 °C above pre-industrial levels (IPCC, 2011). Arguably, one important measure to achieve this ambitious goal lies in substituting fossil-fuel based power generation by an increased use of clean energy technologies (van Vuuren et al., 2011). Clean energy technologies comprise means of energy provision through low-emission and renewable sources, such as solar, wind or biofuels, as well as technologies targeted at raising the efficiency of energy end-use. While these technologies have in common that they significantly reduce the adverse effect of energy consumption on the natural environment, many of them are not yet cost competitive with conventional energy sources, such as coal and gas. Therefore, in the past decades policy makers all over the world have introduced policy measures that aim to foster the development and diffusion of clean energy technologies.
1.2 The Rise of Deployment Policies

Initially, policy measures introduced by governments strongly focused on direct investments in research and development of promising renewable energy technologies. Triggered by the two oil crises in the 1970s, public funding for research was raised significantly, leading to major technological advancements in critical energy technologies, such as solar and wind (Jacobsson and Johnson, 2000). However, over time the strong focus on ‘technology-push’ measures has shifted more and more towards a focus on ‘demand-pull’. While global public investments in R&D related to renewable energy technologies have markedly declined since the early 1980s (Margolis and Kammen, 1999, Smith and Urpelainen, 2013), especially since the 1990s many countries have introduced so-called deployment policies that are targeted at fostering the diffusion of clean energy technologies. In an increasing number of countries, such Germany, Italy and Japan, demand-side incentives for clean energy technologies now outstrip investments in public R&D (REN21, 2012). Market support for solar photovoltaic power in Germany, for example, exceeds public R&D funding by a factor 120 (see Figure 1).

![Figure 1: Annual policy support for solar photovoltaic power in Germany (data from IEA, 2012a, BDEW, 2011)](image-url)

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1 It should be noted that already in the 1970s governments were making use of deployment policies to foster clean energy technologies, e.g., for wind power in California, although to a significantly smaller extent.

2 Only since 2003 has public R&D for energy sources other than fossil fuels started to rise again. Still, levels of R&D spending have never reached the level of the late 1970s (Smith and Urpelainen, 2013).
Deployment policies can take different forms, ranging from fiscal incentives and public finance to market regulations (IRENA, 2012). Fiscal incentives comprise grants or tax credits which lower the initial cost of technology investment for operators of clean energy plants. Public finance incentivizes the use of clean energy technologies by providing guarantees or low-interest loans. Instruments for market regulation, in turn, can be divided into volume- and price-driven instruments. Volume-based instruments, such as renewable portfolio standards or quotas, set a target for the amount of renewable electricity a sector or firm needs to produce at a particular point in time. Usually, instruments are designed in a way that in case of missing the quota, the respective entity is required to pay a penalty, thereby creating an economic incentive for investments in clean energy sources. In contrast, price-based instruments, such as feed-in tariffs, incentivize the use of clean energy technologies by guaranteeing power generators a fixed price above market prices at which they can feed renewable electricity into the grid. Overall, by early 2012 109 countries had implemented policies to support the generation of renewable electricity (IRENA, 2012). As shown in Figure 2, especially the instrument of feed-in tariffs has found widespread diffusion and is now used in more than 65 countries in the world (REN21, 2012).

![Figure 2: Number of countries with feed-in tariff systems and renewable portfolio standards (data from REN21, 2011, REN21, 2012)](image-url)
1.3 Deployment Policies: A Means to Foster Technological Innovation?

Mainly due to demand-side subsidies, the installed renewable power generation capacity (excluding hydro power) has risen by 144 percent in only six years from 160 GW in 2005 to 390 GW in 2011 (REN21, 2012, REN21, 2005). Deployment policies have thus proven a highly effective means of bringing clean energy technologies to the market in the short to medium term. However, at the same time many clean energy technologies remain far from being cost competitive with fossil fuel based energy sources. Supporting the wide-spread deployment of technologies that are not economically viable requires considerable public funds which are generally not available in developing countries. Hence, in the longer run for renewable energies to assume a large share in the global market for energy technologies, it seems indispensable that clean energy technologies reach a cost level at which they can compete with conventional energy sources without policy support. Given the strong focus of policy makers on demand-side instruments in recent years, a critical question to ask is whether and to which extent deployment policies have promoted technological advancement in clean energy technologies beyond a mere diffusion of existing technologies. If the effect of deployment policies was indeed limited to bringing existing concepts to the market, policy makers might be better advised to invest their funds in research and development to bring technologies closer to competitiveness instead of subsidizing their widespread use.

1.4 Research Framework

Amid the strong prevalence of deployment policies in recent years and the need for technological progress in clean energy technologies, this thesis addresses the overarching research question how deployment policies affect, and are affected by, innovation in clean energy technologies. For this purpose, this work draws on both qualitative and quantitative methods to analyze the dynamics and effects of deployment policies in the solar photovoltaic (PV) industry. Figure 3 shows the overarching research framework underlying this work. As can be seen, this work puts a particular emphasis on trying to better understand the detailed effect of deployment policies on firms and their investments in technological learning as a variable mediating the relationship between policy and technological innovation. Moreover, as an important difference to previous studies, this research does not assume policies to be exogenously given but studies how they are affected by — rather than only affect — technological change. Towards these ends, this thesis takes an interdisciplinary approach, combining insights from the fields of economics, organizational theory and innovation studies. While these disciplines differ in their specific focus and assumptions, each possesses particular strengths, which in combination can help generate novel insights into the relationship between deployment policies and technological innovation.
The remainder of this thesis is structured as follows: As a useful starting point, Section 2 provides an overview of the relevant literature. Building upon this, Section 3 points to a number of gaps in the extant literature which serve to define the more detailed objectives of this thesis. Sections 4 and 5 introduce and motivate the research case and methods. A summary of the four papers addressing the individual research questions is presented in Section 6. Finally, Section 7 discusses the implications of this thesis for the existing literature, policy makers and corporate managers and points to avenues for future research.
2 Theoretical Background

This section provides an overview of the relevant literature. To address the overarching research question of this thesis derived in the previous section, this work draws on three main bodies of literature: 1) The literature dealing with the effect of deployment policies on innovation, 2) the literature on firm-level technological learning and 3) the literature on innovation systems. The necessity to discuss previous work studying the effect of deployment policies on technical innovation follows directly from the research question. The main insights from this literature will be presented in Section 2.1. The literature on firm-level technological learning is introduced in Section 2.2 to provide a more nuanced perspective on the different mechanisms through which firms may engage in technological innovation. As will be seen in Section 3, a better understanding of how firms translate policy incentives into corporate investments can help to generate novel insights about how deployment policies affect the rate and direction of technological change. Finally, Section 2.3 discusses the literature that takes a systemic perspective on innovation. This literature is important as it helps to understand the broader implications of policy-induced technological learning, specifically how corporate investments in technological learning may benefit other firms, how technological innovation in a particular technology affects complementary technologies and how technological progress might feed back into changes in the policy itself.

2.1 Deployment Policies and Technological Innovation

The effect of deployment, demand-side or demand-pull policies\(^3\) on technological innovation has been discussed in two main streams of literature: a) the literature on environmental policy and b) quasi-evolutionary, systemic approaches to policy-making. As will be discussed in the following, these two areas of research differ strongly with regard to their underlying assumptions and the rationale for policy intervention.

2.1.1 Environmental Policy

The literature on environmental policy builds upon the assumption that environmentally benign innovation suffers from a so-called ‘double externality problem’ (Jaffe et al., 2005). Following the reasoning of Arthur C. Pigou, who in 1920 was among the first to point out that private and social costs of economic activity are not necessarily congruent, it is suggested that in many instances

\(^3\) In this work, these terms are used interchangeably.
environmental side effects of economic activity, such as pollution or the depletion of natural resources, are not sufficiently reflected in market prices (Baumol and Oates, 1988). As the second externality, it has been argued that firms that invest in innovation can suffer from so-called knowledge spillovers to other firms which is due to the fact that knowledge possesses features of a public good (Griliches, 1992). Since this reduces the possibility for firms to appropriate the benefits from innovative activity, social benefits from innovation have frequently been found to outweigh private benefits – often by several orders of magnitude (Griliches, 1990, Nadiri, 1993). It has been pointed out that, as a result of this, firms may systematically underinvest in innovation compared to the socially optimal level (Arrow, 1962).

To compensate these market failures, the literature on environmental policy suggests that policy makers introduce regulatory measures that support the development and diffusion of environmental technologies (Horbach, 2008). In this context, scholars have recently started to integrate findings from the broader literature on technological change and suggested demand-side measures as an important complement to supply-side instruments (Jaffe et al., 2005, Jaffe et al., 2003, Rennings, 2000, Taylor, 2008). A key objective has been to identify those policy instruments that most efficiently foster the diffusion of environmental technologies. Hence, environmental policy scholars have invested considerable effort in evaluating different instruments that directly or indirectly affect technology deployment, such as technology standards, tradable permits, feed-in tariffs or public procurement (Jaffe et al., 2002, Jänicke and Lindemann, 2010, Edler and Georghiou, 2007, Stavins, 2003). Since often the effectiveness and efficiency of policy instruments are strongly influenced by their idiosyncratic design features, studies have shown a remarkable degree of ambiguity in the assessment of individual instruments (Vollebergh, 2007, Kemp and Pontoglio, 2011). Nevertheless, in line with the debate on the drivers of technological innovation, there is a widespread consensus in the literature on environmental policy that demand triggered by deployment policies induces innovation (Newell et al., 1999).

The idea that environmental regulation can spur innovation is also a central argument in what has become known as the ‘Porter Hypothesis’ (Porter and van der Linde, 1995). Specifically, Porter and van der Linde (1995, p. 98) argue that “properly designed environmental standards can trigger innovation” (Porter and van der Linde, 1995, p. 98). Yet, the argument of Porter and van der Linde (1995) goes beyond the one of other studies in that they maintain that environmental policies may create “absolute [competitive] advantages [for domestic firms] over firms in foreign countries not subject to similar regulations” (Porter and van der Linde, 1995, p. 98). As a reason for this proposition, they argue that environmental regulation may enhance innovation by reducing investment uncertainties and signaling companies about resource inefficiencies. This view is echoed by the literature on so-called “lead markets” which suggests that policy makers can create domestic
markets that allow firms to develop and export environmental technologies (Beise and Rennings, 2005, Jänicke and Jacob, 2004).

### 2.1.2 Quasi-Evolutionary Approaches to Policy-Making

In contrast to the literature on environmental policy, which only recently has begun to integrate findings from the debate on technical change, quasi-evolutionary approaches to policy-making directly derive from evolutionary perspectives on technological change. Evolutionary theories of technological change build upon two main assumptions. First, it is assumed that actors are boundedly rational, possess limited information and limited foresight (March and Simon, 1958, Cyert and March, 1992, Simon, 1947). In their decision-making actors draw on routines (i.e., standardized patterns of action) that allow them to satisfice, i.e., take decisions that are based on localized search and yield satisfactory, rather than optimal outcomes (Nelson and Winter, 1982). Since actors possess neither full information nor foresight, a particular emphasis in evolutionary approaches is put on learning, which allows actors to improve their knowledge (and routines) over time (Malerba, 1992). As a result, information asymmetries between different economic agents are not seen as externalities that distort the efficiency of the market but essential prerequisites for entrepreneurial activity and learning, both of which constitute pivotal drivers of economic progress (Richardson, 1960). Second, the idea of limited information is also reflected in a conception of technology that differs from the one found in the literature on environmental policy. Whereas in the latter literature knowledge is often considered a public good that is effortlessly transferred between firms (see previous section), evolutionary approaches typically stress the complex, contextual and often tacit nature of knowledge, which is closely intertwined with the routines of the actors that develop and apply it (Winter, 1987).

In line with the assumptions described above and in contrast to the literature on environmental policy, political interventions in evolutionary approaches have not been justified with the need to correct for externalities or managerial information deficiencies in an otherwise efficient market (Metcalfe, 1994, Nill and Kemp, 2009). More generally, it is reasoned that policy makers can make use of demand-side policies to shape innovation systems and foster technological learning (Malerba, 2009). Moreover, an important motivation for policy interventions in quasi-evolutionary approaches is their ability to contribute to breaking technological lock-ins (Unruh, 2002).

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4 The reasoning of Porter and van der Linde (1995) in many ways is based on ideas that resemble those expressed in evolutionary studies. Still, most of the empirical studies that have tried to test the ‘Porter Hypothesis’ have been conducted by researchers in the field of environmental policy, rather than scholars interested in technological change (Ambec et al., 2011).

5 It should be noted that originally it was evolutionary economists who developed the notion of knowledge as a ‘public good’ (Nelson, 1959). However, more recent work building upon the tradition of evolutionary economics has raised serious doubts about the public nature of knowledge (Winter, 1987).
Technological lock-ins can occur for a variety of reasons. As pointed out by Arthur (1989, 1988) and David (1985) technologies may be subject to increasing returns to adoption that result from learning by using, network externalities, economies of scale in production, informational increasing returns and technological interrelatedness. Besides these predominantly economic factors, lock-ins may also be forged and cemented through formal and informal institutions, such as industry standards, societal norms, customer preferences or legal frameworks (Geels, 2004, Unruh, 2000). Lock-ins provide socio-technical systems with stability, thereby contributing to their efficiency and predictability. On the negative side, however, technological search under a lock-in situation may become highly localized and incremental in nature (Unruh, 2000). Therefore, especially when technological change is perceived as moving too slow or in the wrong direction, political interventions might become necessary that break the technological lock-in. Recent studies concerned with the question of how to achieve such a ‘lock-out’ have pointed to an important role of deployment policies. According to the frameworks of ‘strategic niche management’ (Kemp et al., 1998, Schot et al., 1994, Hoogma et al., 2002) and the ‘multi-level perspective’ (Geels, 2002, Kemp, 1994, Schot et al., 1994, van den Ende and Kemp, 1999), for example, a key measure for fostering the development of radically different alternatives to existing technologies lies in the creation of so-called niche markets. Niche markets are ‘protected spaces’ in which younger technologies do not stand in direct competition with dominant technologies such that they can develop and eventually disrupt the existing socio-technical regime (Schot et al., 1994, Smith and Raven, 2012). To aid the generation of such spaces and support the scaling up of young technologies, several authors in this field have suggested the use of deployment policies (Faber and Frenken, 2009, Kemp et al., 1998, Smith et al., 2005, Unruh, 2002).

2.2 Firm-Level Technological Learning

As pointed out in Section 1.4, one of the main objectives of this thesis is to generate a better understanding of how deployment policies affect firms and their investments in technological learning. As a result, a second important area of research to be reviewed in this section is the literature dealing with the antecedents and outcomes of technological learning at the firm level.

Firms have always played prominent role in the literature on technical change as “under modern capitalism business firms have become a central locus of efforts to advance technologies” (Dosi and Nelson, 2010). Already Schumpeter (1942, 1912) saw firms as critical actors for innovation and tried to link innovative outcomes to firm characteristics. His assertions that innovation is primarily driven by entrepreneurs (so-called Schumpeter Mark I) or large, monopolized firms (so-called Schumpeter Mark II) have sparked a long debate in the literature on technical change about the
antecedents and outcomes of firm-level technological innovation (for a comprehensive review, see Ahuja et al., 2008, Cohen, 2010). Economic studies have typically focused on well-observable features of firms as an explanation for their innovative activity, such as firm size (Cohen, 2010). Research within the field of management science and organizational theory has gone beyond economic studies in taking a closer look at the inner workings of firms as an explanation for inter-firm differences in innovative activity. In this context, it has been pointed out that firms can draw on different modes of learning which can be assumed to have different effects on the rate and direction of innovative output at the firm level. March (1991, p. 71), for example, suggests that firms can make use of two generic forms of learning: 1) Exploration, which comprises “search, variation, risk-taking, experimentation, play, flexibility, discovery, and innovation” and 2) exploitation, which is defined as “refinement, choice, production, efficiency, selection, implementation and execution”. March suggests that both forms of learning constitute a trade-off since at each point in time they compete for scarce organizational resources. To be competitive in the longer run, however, he stresses that firms need to make use of both exploration and exploitation, especially since the two modes of learning are mutually enabling over time (Farjoun, 2010, Lavie et al., 2010).

The latter notion that firms need to find a balance between exploration and exploitation has become known as ‘ambidexterity’ (Tushman and O’Reilly, 1996, He and Wong, 2004, Birkinshaw and Gibson, 2004). It is proposed that firms can simultaneously reap the benefits of both forms of learning by setting up specialized organizational units (e.g., R&D departments) or switching between the two modes depending on the context over time (Gibson and Birkinshaw, 2004, Tushman and O’Reilly, 1996). Still, it has been pointed out that the balance between exploration and exploitation is not equal for all firms but depends on a number of firm-internal and firm-external factors (Lavie et al., 2010, Jansen et al., 2006, Raisch and Birkinshaw, 2008, Simsek, 2009). In this context, for example, the balance between exploration and exploitation has been found to depend on market dynamism (Kim and Rhee, 2009, Jansen et al., 2006), competitive dynamics (Levinthal and March, 1993, Lewin et al., 1999) as well as firm resources (Cyert and March, 1992, Nohria and Gulati, 1996) and capabilities (Greve, 2007).

As one particularly important factor enabling firm-level technological learning, the literature has identified the firm’s absorptive capacity (Cohen and Levinthal, 1990), defined as the “set of organizational routines and processes by which firms acquire, assimilate, transform and exploit knowledge” (Zahra and George, 2002, p. 186). By describing a firm’s ability to both explore and

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6 Indeed, Scott (1984) demonstrated for a sample of 3388 business units in 437 firms that after controlling for business unit size and industry variables firm fixed effects explain about half of the variance in R&D. This raises the question, which idiosyncratic features affect innovative activity in firms.
exploit knowledge from its environment, absorptive capacity is directly related to March’s dichotomy. While a high ‘potential absorptive capacity’ enhances a firm’s ability to engage in exploration, the firm’s capacity to also exploit the externally acquired knowledge has been termed ‘realized absorptive capacity’ (Zahra and George, 2002). The degree to which a firm can successfully absorb and exploit external knowledge depends on its organizational structure (van den Bosch et al., 1999, Lenox and King, 2004, Jansen et al., 2005), the source of knowledge (Schmidt, 2010) and the proximity between firm-internal and firm-external knowledge (Nooteboom et al., 1998, Lane and Lubatkin, 1998). Generally, however, empirical studies have shown that the level of absorptive capacity of a firm is strongly related to its prior investments in knowledge (Cohen and Levinthal, 1990). A larger endowment of a firm with knowledge that is complementary to external knowledge improves a firm’s capacity to appropriate outside knowledge from other firms and translate it into technological innovations (Lane et al., 2006, Tsai, 2001, Deeds, 2001).

2.3 Innovation Systems

A third area of research which serves as a building block for this thesis is the literature assuming a systemic perspective on innovation. The literature on ‘systems of innovation’ has its origins in the mid-1980s and was devised as an alternative to neo-classical approaches in explaining the industrial competitiveness of countries (Sharif, 2006). In this literature, innovation is seen as the result of a complex interaction between a large number of heterogeneous actors who build formal and informal networks and are embedded in a broader institutional framework. Innovation systems have been studied on different levels of analysis: the nation (Nelson, 1993, Freeman, 1988, Lundvall, 1992), the sector (Malerba, 2002, Breschi and Malerba, 1997), the region (Saxenian, 1996) and the technology (Carlsson and Stankiewicz, 1991, Carlsson, 1997, Carlsson and Jacobsson, 1994). Whereas for example, the national innovation systems approach analyzes and compares actors, institutions and networks in different countries, the technological innovation systems (TIS) approach takes a specific technology as a starting point to study the conditions and processes that give impetus to its development and diffusion (Markard and Truffer, 2008). Moreover, the approaches especially differ in their definition of ‘institutions’. The literature on national and sectoral innovation system focuses on the analysis of formal institutions (such as regulations, industrial standards) and includes in this term political and scientific agencies (Nelson, 2008). The literature on technological innovation systems, in contrast, also considers informal institutions, such as social legitimacy, which is why TIS are explicitly labeled socio-technical systems (Bergek et al., 2008). Notwithstanding their different foci, the different innovation system approaches are closely related in that they study the flows of information, goods, human resources and capital between
firms, their suppliers, competitors, customers as well as scientific, financial and regulatory agencies. The degree of innovation found in the system is then explained by the relative presence or absence of particular system elements as well as their interconnections and complementarities. The TIS approach, for example, identifies a number of ‘functions’ or ‘key processes’ that need to be present in the system for it to effectively support the development and diffusion of a technology (Bergek et al., 2008; Hekkert et al., 2007). In the taxonomy of Bergek et al. (2008) these processes include ‘knowledge development and diffusion’, ‘influence on the direction of search’, ‘entrepreneurial experimentation’, ‘market formation’, ‘legitimation’, ‘resource mobilization’ and ‘development of positive externalities’. Policy makers wishing to enhance the performance of the innovation system should identify mechanisms inducing or blocking these functions and implement policy measures to remove potential bottlenecks.
3 Objectives

As stated in Section 1.3, the overarching objective of this thesis is to address the question *how deployment policies affect, and are affected by, innovation in clean energy technologies*. While much progress has been made in studying the effects of demand and deployment policies on technological innovation (see previous section), several important aspects remain under-investigated. Figure 4 revisits the overarching research framework presented previously and indicates four important areas of research that so far have received limited attention (see black markers). In this thesis, each of these four areas is addressed by one paper. In the following, the research questions of each of the papers will be motivated by pointing to shortcomings in the existing literature.

![Figure 4: Research framework](image)

3.1 Paper I: The Mechanisms Linking Deployment Policies and Corporate Investments in Technological Learning

The first paper of this thesis addresses the question how deployment policies affect corporate investments in technological exploration and exploitation. As described in Section 2.1, there is a broad consensus in the literature that demand and deployment policies can induce innovation. However, while both the literature on environmental policy and quasi-evolutionary approaches to policy-making stress the importance of demand-side policies, we currently lack a *detailed understanding of the mechanisms* through which deployment policies induce innovation. Environmental policy scholars investigating the effect of demand-side policies usually measure...
innovation on the sector level, drawing on indicators such as patents or R&D investments (Cleff and Rennings, 1999). While these studies have provided much evidence that deployment policies can induce innovation, they provide no insights into the firm-level dynamics that mediate political demand-side incentives and the observed positive innovation effect (Ambec et al., 2011). Quasi-evolutionary approaches to policy making have a much firmer grounding in the micro processes of technical change in that they stress complex interactions between a large number of heterogeneous actors as the drivers of innovation (see Section 2.1.2). Yet, empirical studies in this field usually take a system perspective and do not focus on how policy induces specific actors, such as firms, to invest in innovative activities (Nill and Kemp, 2009, Dosi and Marengo, 2007).

Recent studies stress the importance of investigating the influence of deployment policies on a more disaggregated level, e.g., the firm, since innovation may result from different modes of technological learning (see Section 2.2), which may differ in their effects on the rate and direction of innovation and might be differently triggered by deployment policies (Malerba, 2009, Hendry and Harborne, 2011, March, 1991). Nemet (2009), for example, shows that policy-induced demand coincided with a decline in patenting activity in the US wind industry in the 1980s. He presents several possible explanations for this intriguing finding. As a particularly appealing proposition he suggests that the market created by deployment policies may have incentivized producers of wind power technology to ‘exploit’ existing products to benefit from learning by doing and economies of scale, while discouraging them to ‘explore’ alternative technological options.

Malerba (2009, p. 36) points out that exploitation is likely to lead to “small modifications in existing technologies and a focus only on incremental innovations”. Moreover, he emphasizes that a strong focus of firms on exploitation “may end up locking an industry into a given technology” (p. 37). Given that in the extant literature deployment policies are primarily seen as instruments for breaking lock-ins (see Section 2.1.2), the idea that they might also contribute to their occurrence calls for a more detailed investigation of the exact mechanisms through which deployment policies affect firms within an industry. While anecdotal evidence suggests that deployment policies affect the degree to which firms focus on technological exploitation and exploration, it remains unclear whether deployment policies in fact induce exploitative behavior and enhance the risk of a technological lock-in. Although the literature on organizational learning has identified various antecedents of firm-level exploration and exploitation (see Section 2.2), thus far there are no empirical studies available that investigate the impact of public policy (Lavie et al., 2010).
3.2 Paper II: The Role of Inter-Firm Knowledge Spillovers for Innovation in Environmental Technologies

While the first paper investigates the link between deployment policies and corporate investments in technological learning, it leaves open how these investments translate into improvements in the cost-to-performance ratio of technology. Therefore, the second paper sheds more light on the link between corporate investments in technological learning and technological innovation (see no. II in Figure 3). More specifically, the paper addresses the question to what extent innovation in a firm’s environmental technologies is driven by own investments in R&D and knowledge spillovers from other firms in the industry.

The degree to which innovation in environmental technologies is driven by knowledge spillovers has important implications for the debate on whether corporate investments in environmental innovation can spur the competitive advantage of firms. In the literature dealing with ‘organizations and the natural environment’ a number of scholars have suggested that firms which take a proactive stance towards investments in innovation for environmental technologies are able to reap economic benefits (Buysse and Verbeke, 2003, Shrivastava, 1995). Moreover, as discussed in Section 2.1.2, Porter and van der Linde (1995) argue that governments should put in place strict environmental regulations to spur innovation which they believed to enhance the competitiveness of firms residing in their country. This idea is echoed by the literature on ‘lead markets’ which suggests that policy makers can create domestic markets that allow firms to develop and eventually export environmental technologies (Beise and Rennings, 2005, Jänicke and Jacob, 2004).

As alluded to in Section 2.1, there is a broad consensus in the literature that environmental policies can induce firms to invest in technological innovation. The question whether these investments in innovation in turn also lead to a competitive advantage of firms, however, remains controversially debated (Ambec et al., 2011). On the one hand, the economic literature since Schumpeter has continuously pointed to a crucial role of technological innovation for the competitiveness of firms and economic growth (Henderson and Clark, 1990, Christensen and Bower, 1996, Tushman and Anderson, 1986). On the other hand, there are many studies that show how knowledge generated through innovation can spill over to other firms through various channels (Griliches, 1992, Mansfield, 1985). For example, knowledge spillovers are a central building block in the literature on innovation systems (see Section 2.3), as they help explain the occurrence of innovation clusters like the Silicon Valley and the catching up of emerging economies. While knowledge spillovers have positive effects on imitating firms, they simultaneously reduce the degree to which first movers can appropriate the benefits from investments in innovation. Strong knowledge spillovers may thus undermine the short-term competitive advantage a firm or country might be able to generate.
through innovation (McEvily and Chakravarthy, 2002, Lieberman and Montgomery, 1988). This notion is backed by the resource-based view which posits that longer-term competitive advantages of firms are based on resources that, amongst others, are rare and inimitable (Barney, 1991, Wernerfelt, 1984).

Due to their significant influence on firm competitiveness, knowledge spillovers are of importance in all industries. Yet, they play a particularly important role for the case of environmental technologies since a) much more than other technologies they have been subject to targeted policy support and b) in almost all cases a key motivation of policy makers has been to increase the competitiveness of domestic firms. Albeit the potentially important role they might play, inter-firm knowledge spillovers for environmental technologies remain understudied in the extant literature. Previous studies have investigated spillovers between countries and industries (e.g., Bosetti et al., 2008, Nemet, 2012). While bearing interesting implications for policy makers, these studies do not allow deriving implications for the competitiveness of firms. In addition, existing studies provide little insights into the drivers of knowledge spillovers between firms pursuing environmental innovation. As discussed in Section 2.2, the literature on absorptive capacity has shown that firms can enhance their potential for knowledge absorption by building their own, complementary knowledge, e.g., through R&D (Cohen and Levinthal, 1990). Yet, as other authors have pointed out, knowledge can also be transferred through the exchange of people or technological artefacts, such as machinery (Harabi, 1997, Levin et al., 1987). Based on a study of copper interconnect technology for semiconductor chips, Lim (2009) suggests that the type of knowledge firms absorb changes over the technology life-cycle from general scientific knowledge to knowledge embedded in tools and processes. Although this suggests that, besides investments in R&D, investment in machinery might play a role for knowledge absorption, we currently lack systematic evidence of different channels for inter-firm knowledge spillovers in the case of environmental technologies.

3.3 Paper III: The Effect of Technological Change on the Dynamics of Deployment Policies

Together, the first two papers shed light on the detailed effects of deployment policies on technological innovation. However, they do not yet provide any insights into the reverse relationship, i.e., how technological change and related uncertainties affect the dynamics and design of deployment policies. Against this background, the third paper addresses the question how the complex dynamics of socio-technical systems shape the process of policy interventions targeted at inducing technological change.
As discussed in Section 2.3, the literature on technological innovation systems has identified a number of functions or key processes that policy makers should support to foster the development and diffusion of technologies. It is suggested that policy makers measure the extent to which these functions are present within the technological innovation system and identify mechanisms that block or induce their seamless functioning (Bergek et al., 2008). Based on this analysis policy makers should devise technology-specific policies that remove potential bottlenecks (Wieczorek and Hekkert, 2012). While the general usefulness of the functional analysis of TIS has been successfully applied in a large number of empirical settings (e.g., Negro et al., 2008, Suurs and Hekkert, 2009, van Alphen et al., 2010), it seems possible that in reality designing policies targeted at removing the identified bottlenecks may be complicated by the inherent uncertainty of technological change and the complexity of socio-technical systems.

Lindblom (1959) developed the concept of ‘muddling through’ to describe that policy makers usually do not possess the knowledge to accurately foresee all consequences of their action. He suggested that, due to limited information, foresight and bounded rationality, they have to implement policies which may only partially achieve the desired goals. Based on the experience they have gained with their experiment, they can then adjust their policy and learn over time (Lindblom, 1959, Lindblom, 1979, Forester, 1984). The notion that policies implemented will not be perfect from the start may be particularly true when policy makers try to purposefully induce technological change. Technological change evolves in a non-linear, highly unpredictable way, implying that the outcome of policy interventions might be difficult to predict in advance. Moreover, as expressed in Section 2.3, the literature emphasizes the large number of structural elements that are part of (technological) innovation systems which interact through various channels. As a result, policy makers might be able to successfully induce technological change by fostering a particular function of a TIS. Due to complex interdependencies between the elements of TIS, however, removing the bottleneck to a particular function may unexpectedly enhance or generate new blocking mechanisms.

Overall, therefore, it seems possible that the inherent uncertainty of technological change and complexities of socio-technical systems require policy makers to dynamically adjust the design of policies to unforeseen developments. The literature on reflexive governance, for example, suggests that generally policies targeted at fostering sustainability transitions need to be designed in a highly flexible and adaptive way (Voß and Kemp, 2006). The literature on TIS has acknowledged that policy interventions in TIS might have unforeseen effects (Bergek et al., 2008, Bergek and Jacobsson, 2003). Yet, so far, the ramifications of technological uncertainty and the complexity of the socio-technical system for the dynamics of the policy process have not been explicitly addressed in the academic literature.
3.4 Paper IV: The Effect of Policy-induced Technological Innovation on the Economic Viability of Complementary Technologies

Finally, an important question that remains under-investigated is how policy-induced technological innovation affects the economic viability of technologies which are complementary to the one supported by deployment policies. The literature streams on complex products and systems (Hobday, 1998) and large technical systems (Hughes, 1979, Hughes, 1983, Hughes, 1987) provide many examples for technologies, such as airplanes, computers or the electricity system, that consist of a large number of interconnected components. It is pointed out that, due to the interdependencies and complementarities between these components, changes in one part of the system usually have direct effects on others or even require changing the entire product architecture (Henderson and Clark, 1990). Rosenberg (1976), for example, cites the development of steel rails, telegraphs, air brakes and automatic couplers as important preconditions for the successful diffusion of railroad technology. He argues that “growing productivity of industrial economies is the complex outcome of large numbers of interlocking, mutually reinforcing technologies, the individual components of which are of very limited economic consequences by themselves. The smallest unit of observations, therefore, is seldom a single innovation but, more typically, an interrelated clustering of innovations” (Rosenberg, 1983, p. 59). Similar arguments have been brought forward in the literature on technology diffusion. Lissoni and Metcalfe (1994, p. 107), for example, suggest that “[c]ompatibility, inter-relatedness and co-development are emerging as important themes in modern diffusion research. Furthermore, the single innovation is no more seen as the appropriate unit for diffusion analysis. Rather what is being diffused is often a sequence of innovations with an evolving design configuration which itself develops in response to competing and complementary configurations”.

Despite the observation that in many cases technologies are linked to build larger technological systems, extant studies have usually focused on investigating the effect of deployment policies with regard to the particular technology that is directly targeted by policy makers. It seems likely that the diffusion of the technology and the related improvements in its cost-to-performance ratio affect complementary technologies. Since these technologies are often of critical importance for the performance of the overall system, research seems warranted that elaborates on how policy-induced technological change affects the economic viability of complementary technologies.
3.5 Summary of Objectives

In sum, the Sections 3.1 to 3.4 highlighted four areas of research which remain under-investigated in the extant literature. In this thesis, each of the four research gaps is addressed by one paper (see Table 1). The main objective of these papers lies in enhancing our theoretical understanding of the link between deployment policies, technological innovation and vice versa. In this context, the thesis at hand shall especially make contributions to the literature on deployment policies, firm-level technological learning and innovation systems. As a second aim of this thesis, concrete implications for practical decision-making in public policy and corporations shall be derived. It is the explicit goal of this work to provide policy makers with advice on how to design deployment policies in a way that enhances their overall effectiveness. In addition, shedding light on the research questions allows formulating recommendations for the design of corporate strategies in industries that are directly or indirectly affected by deployment policies.

<table>
<thead>
<tr>
<th>Paper</th>
<th>Title</th>
<th>Research Question</th>
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<tbody>
<tr>
<td>I</td>
<td>The Two Faces of Market Support – How Deployment Policies Affect Technological Exploration and Exploitation in the Solar Photovoltaic Industry</td>
<td>How do deployment policies affect corporate investments in technological exploration and exploitation?</td>
</tr>
<tr>
<td>II</td>
<td>The Role of Inter-Firm Knowledge Spillovers for Innovation in Environmental Technologies – Evidence from the Solar Photovoltaic Industry</td>
<td>Which role do inter-firm knowledge spillovers play for innovation in environmental technologies?</td>
</tr>
<tr>
<td>IV</td>
<td>The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems – A Review and a Scenario-Based Optimization Model</td>
<td>When and under which conditions will battery storage be economically viable in residential PV systems without demand-side subsidies for an economically optimized system configuration?</td>
</tr>
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</table>
4 Research Case

To investigate the research questions presented in the previous section, the solar photovoltaic (PV) industry is chosen as a research case. Solar PV is an important clean energy technology which can make significant contributions to mitigating climate change and reducing the adverse impact of the energy sector on the natural environment. Emissions of solar PV over the product lifecycle are much lower than those resulting from conventional means of power generation (Peng et al., 2013, Evans et al., 2009). At the same time, as shown in Figure 5, among all clean energy technologies solar power has by far the largest physical and technical potential\(^7\) for energy generation. In fact, already existing solar technologies could provide 4 to 130 times the current global primary energy demand.

\[\text{Figure 5: Global physical and technical potential of clean energy technologies in relation to global primary energy demand (data from IPCC, 2012, Nitsch, 2007)}\]

\(^7\) The physical potential describes the maximum amount of energy generation that is possible considering physical conditions on earth. The technical potential, in contrast, is defined as the amount of energy generation that is possible using existing technologies.
A major barrier to a more widespread use of PV technology are its costs, which are still significantly higher than those of conventional means of power generation, such as coal or gas (Peters et al., 2011). In order to support the development and diffusion of PV, in recent years policy makers in many countries have put in place support schemes for PV on both the supply and demand side. Driven by deployment policies, the installed capacity for PV has escalated at an annual rate of 34% from a mere 0.5 GW in 1994 to almost 70 GW in 2011 (see Figure 6). The early years saw the US and Japan with the biggest market for photovoltaic products (Watanabe et al., 2000, Algieri et al., 2011). In 2004, Germany amended its Renewable Energy Sources Act which resulted in a surge of domestic installed PV capacity by almost 300 percent compared to 2003. Despite the fact that the physical conditions for solar power in Germany are far from optimal, it has consistently been one of the two largest markets for PV technology since 2004. At the same time deployment policies have also been introduced in a large number of other countries. In line with the overall diffusion of policy instruments like feed-in tariffs and renewable portfolio standards (see Section 1.2), many countries have introduced demand-side incentives for solar PV which has led to the emergence of new markets.

![Figure 6: Development of average selling price of PV modules and global installed PV capacity](data from Navigant Consulting, 2012, Navigant Consulting, 2010, EPIA, 2008, EPIA, 2012)
At the same time that deployment increased, the average selling price of PV modules plummeted from 7.82 USD/Wp in 1994 to 1.37 USD/Wp in 2011 (in real terms). Amid the strong correlation between cost decreases and deployment both practitioners and academic scholars have argued that, similar to the semiconductor industry, costs in the PV industry follow the pattern of learning curves. Indeed, plotting cost developments over cumulative installed capacity of PV on a double-logarithmic scale yields an almost linear relationship with typical learning rates of around 20% (Junginger et al., 2010). The existence of learning curves suggests a high effectiveness of deployment policies in fostering technological innovation for PV technologies. Yet, several questions related to the use of deployment policies in the PV industry remain unanswered that are closely related to the theoretical research gaps presented in the previous section.

First, an important question to ask is whether deployment policies are equally effective in fostering different sub-technologies within PV. In the PV industry, there are a number of different technologies competing for market share, each of which possesses distinct advantages and disadvantages (Photon, 2012). In 2011, with 87% the biggest share of the PV market was made up of wafer-based crystalline silicon (c-Si) PV technologies, followed by thin-film PV (e.g., cadmium telluride, amorphous silicon and copper indium gallium selenide) and emerging PV technologies (e.g., dye-sensitized and organic PV). Being first developed in the 1950s for space applications, wafer-based c-Si is relatively mature and has the highest energy conversion efficiency. Thin-film or emerging PV, however, possess a significantly lower material intensity which might give them a cost advantage in the longer run. Although therefore all PV technologies show promise and merit support, authors have raised concerns that deployment policies might have contributed to locking the PV sector into wafer-based c-Si technologies (Sandén, 2005, Menanteau, 2000, Sartorius, 2005, van den Heuvel and van den Bergh, 2009).

A second question of high relevance is why manufacturers of PV cells and modules located in countries with strong deployment policy support have not been able to generate a longer-term competitive advantage. In many countries the hope of increasing economic competitiveness and generating domestic jobs in a dynamic high-tech industry has been a key motivation for introducing deployment policies for solar photovoltaic power. Still, none of the companies producing PV cells and modules have been able to maintain its leadership position for a longer period of time. Especially in recent years, Chinese firms have significantly increased their share in the production of PV cells from only 4% in 2004 to almost 70% in 2011 (Photon, 2012, Photon, 2005). This rapid catch-up raises the question which role knowledge spillovers might have played in driving changes in leadership positions in the solar PV industry. Anecdotal evidence suggests that the emergence of standardized equipment might have played an important role in driving knowledge spillovers in PV as Western equipment manufacturers have embodied knowledge in their products that had been
gathered during cell production (de la Tour et al., 2011). The fact that this equipment was later exported to Chinese manufacturers might have allowed Chinese firms to quickly enter the market and compete with European, US and Japanese firms.

Third, the question arises whether falling technology costs and rising deployment of PV have triggered changes in the design of deployment policies. As discussed in Section 1.2, there are various deployment policy instruments, all of which have been used by governments in different countries to stimulate the adoption of PV technologies. However, besides varying across countries, approaches chosen to incentivize deployment have also evolved substantially within the countries over time. The German feed-in tariff for solar PV as one of the most effective deployment policy schemes, for example, has been revised 8 times between its introduction in the year 2000 and the end of 2011. Given that the policy scheme has served as a blueprint for other countries, it seems important to shed more light on whether these changes have been driven by developments in the technological sphere and whether future deployment policies will have to be designed in a similarly flexible way to account for technological change.

Finally, it remains open how policy-induced innovation in solar PV alters the economic viability of important complementary technologies, such as battery storage. Electricity generation from PV is highly intermittent in the sense that it is limited to daytimes, depends on local weather conditions and fluctuates over the year (Joshi et al., 2009). Therefore, to guarantee an electricity supply that matches the pattern of electricity consumption, it becomes necessary to implement measures that reduce or eliminate the mismatch between demand and supply (Eltawil and Zhao, 2010). One promising solution to reduce the intermittency of solar PV lies in the use of battery storage (Krause, 2011). Yet, while the possibility of shifting the supply of electricity to different times enhances the value of the electricity produced, adding storage technologies to a PV system also raises the overall investment cost to be borne by plant operators. First countries, like Germany, have therefore have announced programs that support the use of storage technologies for residential PV through investment subsidies (Photon, 2013). Given cost decreases in PV systems and battery storage and influences of other factors, such as electricity prices, the question arises whether and for how long these subsidies are necessary to drive the deployment of storage technologies.
5 Methods and Data Sources

Table 2 summarizes the methods and data sources employed in the four papers of this thesis. As described in Section 3, each of the four papers in this thesis addresses a distinct research question. Since the individual research questions of the papers differ significantly in their nature, this thesis employs a multi-method approach, consisting of both qualitative and quantitative research methods. In the following, the research methods used in the papers will be discussed in more detail. In particular, it will be pointed out why the respective research method was selected, which data was drawn upon and how this data was analyzed to yield the findings presented in the subsequent Section 6.

Table 2: Methods and data sources used in papers

<table>
<thead>
<tr>
<th>Paper</th>
<th>Title</th>
<th>Method</th>
<th>Data Sources</th>
<th>Geogr. Scope</th>
<th>Time Scope</th>
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<tbody>
<tr>
<td>I</td>
<td>The Two Faces of Market Support – How Deployment Policies Affect Technological Exploration and Exploitation in the Solar Photovoltaic Industry</td>
<td>Qualitative: Case study</td>
<td>Data from interviews with 24 managers of 9 firms producing PV modules and 16 PV industry experts</td>
<td>Global</td>
<td>2004 – 2011</td>
</tr>
<tr>
<td>II</td>
<td>The Role of Inter-Firm Knowledge Spillovers for Innovation in Environmental Technologies – Evidence from the Solar Photovoltaic Industry</td>
<td>Quantitative: Panel data regression</td>
<td>Data from annual reports of 23 publicly listed producers of wafer-based crystalline silicon PV cells and industry reports</td>
<td>Global</td>
<td>2000 – 2011</td>
</tr>
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5.1 Paper I: Interview-based Comparative Case Study

To investigate how deployment policies affect corporate investments in technological exploration and exploitation in paper I, we used a qualitative case study approach. According to Eisenhardt (1989) and Yin (2009) qualitative case studies allow studying a phenomenon at a great level of
detail under consideration of the specific context it is embedded in. Therefore, they are particularly well suited for the exploratory phase of research in areas for which little empirical research exists. As described in Section 3.1, currently, there is no research that has explicitly investigated the link between deployment policies and investments in technological exploration and exploration at the firm-level. As a result, case studies were considered an appropriate method to explore potential causal mechanisms between the constructs and build theory in an inductive way.

In line with previous studies that have applied March’s framework in the context of technological innovation (e.g., He and Wong, 2004, Greve, 2007) for our study we defined exploration as *all innovation activities pertaining to the generation of new technological options for the firm’s product portfolio*, i.e., in our work exploration is strongly related to investments in R&D. Exploitation we operationalized as *all innovation activities related to the execution of a firm’s existing product portfolio*, i.e., primarily investments in production capacity and manufacturing. We were particularly interested in how corporate investments in exploration and exploitation are triggered by policy-induced market growth, defined as the *annual increase in market size induced by a deployment policy*. Moreover, a focus in our work was to investigate how firm and technology characteristics moderate the link between deployment policies and corporate investments in technological learning.

Data was gathered and analyzed in three steps: First, to obtain a solid understanding of the context, secondary data on the PV industry, such as annual reports of publicly listed producers of PV cells and modules as well as press articles were collected using desk research. Second, a first round of interviews with 16 designated PV industry experts with a broad range of different backgrounds (e.g., policy makers and investors) was conducted. This served to develop preliminary propositions on the links between deployment policies and corporate investments in the PV sector. Third, as the main data source, we conducted interviews with 24 representatives from 9 companies developing and producing PV modules. These companies were selected such that they pursued PV technologies at different stages of the technology life-cycle, were located in different geographic regions and differed in size as all of these factors were considered potential factors moderating the relationship between deployment policies and corporate investments (Algieri et al., 2011, Peters et al., 2012). We especially contacted company representatives holding positions in general management, R&D, production, policy or strategic marketing departments since employees in these roles were assumed to possess the best knowledge of our phenomenon of interest. All interviews were semi-structured, lasted between 45 to 90 minutes and were prepared using intensive desk research. To ensure a high level of internal, external and construct validity, whenever possible, we interviewed at least two firm representatives and validated statements in additional expert interviews (Eisenhardt and Graebner, 2007, Gibbert et al., 2008).
After transcribing the interview data from records or handwritten notes, the data was analyzed using analytical induction (Manning, 1982). For this purpose, after each interview transcripts were independently reviewed by three researchers. Drawing on the qualitative data analysis software ATLAS.ti, interview statements referring to relationships between different constructs were likened to our theoretical research framework. In case of deviations between our expectations and findings, the constructs and propositions of our framework were then adjusted to increase the construct validity and internal validity of our framework (Gibbert et al., 2008). Using this procedure, the framework was continuously improved until the marginal gain in theoretical insights became small (Eisenhardt, 1989).

5.2 Paper II: Panel Data Regression Analysis

Paper II investigates the role of inter-firm knowledge spillovers for innovation in environmental technologies. Since there is a long literature describing the channels and effects of knowledge spillovers, in contrast to paper I, the main goal of paper II is not to build new theory but to test a number of well-founded hypotheses. Specifically, we phrased four hypotheses pertaining to the role and drivers of knowledge spillovers for innovation in environmental technologies. Hypotheses 1a and 1b suggest that knowledge developed by other firms in an industry positively affects innovation in a firm’s environmental technology (1a) but that this knowledge spillover effect on innovation is smaller than the direct effect of internally developed knowledge (1b). A second set of hypotheses then tested possible factors moderating knowledge spillovers. In line with the literature on absorptive capacity, we expected knowledge spillovers to be positively moderated by a firm’s prior knowledge generated through R&D (hypothesis 2a). Moreover, we tested the hypothesis that knowledge spillovers might have been driven by firms’ investment in manufacturing equipment (hypothesis 2b). To test these hypotheses, we used quantitative panel data regression analysis on data from a sample of 23 publicly listed producers of wafer-based crystalline silicon PV cells for the time from 2000 to 2011.

Companies in the sample were identified based on Breyer et al. (2010) and Photon (2012). To ensure a minimum technological proximity between firms, only companies producing crystalline silicon PV were considered for the analysis. Furthermore, firms had to at least cover the value chain step of cell production since this step is one of the most technologically challenging with large potential for innovation. Collectively, in 2011 the firms in our sample produced 52.1% of all PV cells. Since the data we required for our analysis is generally not reported by conglomerates, all firms in our sample are pure-play manufacturers of PV cells.
Data was taken from annual reports, SEC filings, Photon (2012), Breyer et al. (2010) and the International Energy Agency (IEA, 2012a). In line with the literature dealing with innovation in the energy sector, innovation in PV cells as the dependent variable was measured as an improvement in their cost-to-performance ratio in USD per watt peak (Wp) (Suntech Power Holdings Co., 2012). Product prices in USD/Wp were directly extracted from annual reports and SEC filings or calculated by dividing the company’s sales in USD by its sales volume in Wp. These prices were then translated into costs using the firm’s gross profit margin. The knowledge stocks of firms as the independent variable were constructed from data on annual R&D investments (see e.g., Kaiser, 2002). For the 23 firms in our sample, this data was obtained directly from annual reports and SEC filings. To obtain a measure of private R&D investments external to the firm, we drew on data from Breyer et al. (2010) who estimated annual private R&D expenditures in the PV industry over time based on patent data. All knowledge stocks were constructed using various knowledge depreciation rates ranging from 0% to 40% and time lags of 1, 2, 3, 4 and 5 years for firm-internal knowledge and 3, 4, 5, 6, and 7 years for firm-external knowledge respectively (Watanabe et al., 2002).

To identify controls for the model, we conducted a comprehensive literature review and solicited industry experts. Based on this procedure, knowledge from public R&D, the firm’s production capacity (in MW), cumulative production (in MW), raw silicon costs (in USD per kg), the USD exchange rate and the firm’s vertical integration were included as factors affecting firm-level changes in the cost and performance of PV cells (see also Nemet, 2006). Data on public R&D investments in the PV industry was taken from IEA’s “Energy technology research and development” database (IEA, 2012a) which reports R&D data for 15 OECD countries since 1975, thereby covering about 80 to 90% of the global public R&D investments in recent years (Breyer et al., 2010). Data on the remaining variables was obtained from annual reports, SEC filings, Photon (2012), Bloomberg and OANDA (2012) respectively. To account for the fact that newly installed equipment is operational only after around one year, similar to the independent variables, production capacity and cumulative production were lagged by 1 to 3 years.

The panel data set was analyzed using firm-fixed effects regression analysis. After estimating a model that only included controls, we first added our independent variables and then included interaction terms to test for the moderating effect of the firm’s prior knowledge and investments in production equipment on knowledge spillovers. All variables, except the dummies used as controls for vertical integration, were included in logarithmic form to account for diminishing marginal effects of the independent variables on innovation (Griliches, 1998) and bring the data closer to normal form. In addition, to avoid biases in the estimated standard errors, we employed autocorrelation and heteroscedasticity robust estimation techniques.
5.3 Paper III: Longitudinal Case Study based on Archival Data

As discussed in Section 3.3, paper III investigates how the complex dynamics of socio-technical systems shape the process of policy interventions targeted at inducing technological change. Understanding the detailed dynamics of policy making requires an in-depth understanding of the context and mechanisms at work. Therefore, similar to paper I, in paper III we employed a qualitative case study approach to examine the evolution of the German feed-in tariff system for solar photovoltaic power from 1990 to 2011 (Yin, 2009, Eisenhardt and Graebner, 2007). This case was chosen since the German feed-in tariff has proven very effective in increasing the deployment of renewable energy technologies and has served as a blueprint for FIT schemes in other countries. In 1990, Germany was the second country to adopt this instrument and has since then shown a remarkable continuity in its use. The long time horizon over which developments can be traced in the German case facilitates an in-depth analysis of drivers and effects of policy.

Similar to paper I, in a first step we used semi-structured interviews with PV industry experts to understand the broader context of our research case. Of the 21 experts we interviewed, 7 were directly involved in the legal process since they served as members of the German Bundestag (the national parliament), worked in the ministry of environment or functioned as experts for expert committees. In a second step, as the main data source, we then conducted a comprehensive analysis of more than 700 archival documents. For this purpose, we first collected all legislative texts of the German Renewable Energy Sources Act (EEG) with its 8 amendments. To understand the policy process behind the changes in legislation, we then searched the online archive of the German Bundestag. A search for the key words ‘solar’, ‘solar energy’, ‘solar power’, ‘sun power’ and ‘photovoltaic’ (in German) yielded 715 documents of which we discarded 170 since they contained little or no useful information. Besides these documents, additional data was compiled from secondary data sources, such as the industry magazine “Photon” and external evaluation reports. This served to be able to assess the effects of the policy measures on the broader socio-technical system, e.g., in terms of PV deployment, industry development, jobs and social costs.

To enhance our theoretical understanding of the drivers and outcomes of policy interventions targeted at inducing technological change, we analyzed our data using qualitative content analysis. In a bottom-up, iterative coding procedure, we first identified prevalent issues in the policy debate, mentioned as rationales for policy implementation. Overall, we found 2,354 text elements which we clustered into 15 issue categories. Subsequently, we applied pattern matching (Yin, 2009) to link the issues with implemented policy measures and developments in the broader socio-technical system. This procedure allowed us to infer whether and how changes in issues led to changes in the German feed-in tariff system, how modifications in the policy design affected the socio-technical
system and how changes in the system configuration were linked to the emergence of new issues in the political debate. The insights generated in this process, in turn, served as the basis for developing a process model which describes how policy-induced technological change drives changes in the design of policies.

5.4 Paper IV: Scenario-Based Techno-Economic Model

Finally, paper IV investigates when and under which conditions battery storage will be economically viable in residential PV systems without demand-side subsidies for an economically optimized system configuration. In contrast to the other papers in this dissertation, the time scope of this analysis is forward-looking. To address our research question, we therefore drew on a scenario-based, techno-economic model that simulates the profitability of storage for a residential PV system in Germany under eight different electricity price scenarios from 2011 to 2020. Battery storage raises the share of electricity generated by its own PV system a household can consume. Since this reduces both the volume of electricity that needs to be bought at retail prices and the one to be sold at wholesale prices, owners of integrated PV-storage systems can leverage the existing spread between wholesale and retail prices (Bost et al., 2011, Braun et al., 2009, Colmenar-Santos et al., 2012). In our model, we investigate whether and when, given falling technology costs for PV modules and battery storage, this benefit of storage outweighs initial investment costs. In contrast to previous studies and the current situation in Germany, we assume that no feed-in or self-consumption premiums are paid for electricity generated from PV systems. Moreover, we optimize the size of both the PV and the storage system such that for the investment year the household maximizes the net present value (NPV) of its investments.

Technological input parameters in the model were chosen such that they match the situation of a three-person household in Stuttgart, Germany, that invests in crystalline silicon PV technology with lead-acid battery storage. We focus on crystalline silicon PV as this technology offers higher conversion efficiencies than thin-film PV and is therefore best suited for residential applications. Lead-acid battery technology was chosen since, in the view of their high reliability, low self-discharge as well as low investment and maintenance costs it is currently the most economic technology in small-scale applications (Jenkins et al., 2008, Sauer et al., 2011, Nair and Garimella, 2010). Economic input parameters, such as the investment costs for the PV system and battery storage and electricity prices, were retrieved from annual reports of PV module producers, industry reports and expert interviews. In line with the literature, technology costs for the PV system were extrapolated using learning curve methodology. For forecasts of future battery costs we relied on VDE (2009). Since the future development of electricity prices is highly uncertain, we ran our
model for eight alternative price developments. Moreover, uncertainties in the model assumptions were addressed by conducting a comprehensive sensitivity analysis.

The model itself consists of three main modules: 1) the self-consumption calculation module, 2) the net present value calculation module and 3) the storage and PV size optimization module. The self-consumption module calculates the share of electricity generated by the PV system that is consumed by the household as a function of the PV system and battery storage size. The calculated self-consumption ratio serves as an input to the second module which, for a given investment year calculates the NPV of household investments as the sum of the discounted cash in- and outflows over the 25 year lifetime of the PV system. While cash outflows consist of the investment and maintenance costs for the PV and battery system, cash inflows are calculated as the electricity generated by the PV system multiplied with the retail and wholesale prices respectively (depending on whether the electricity is self-consumed or sold to the grid). The calculated NPV is input into the third module which for each investment year and each of the eight electricity price scenarios tests 1,435 different configurations of the integrated PV-storage system to maximize the household return. Following this procedure allowed us to identify the PV system and storage sizes that maximize the net present value of investments for each of the years 2011 to 2020. By comparing the optimal storage and PV system size for different scenarios, finally, we were able to assess the influence of external factors, such as electricity wholesale and retail prices, on the economic viability of storage for residential PV systems.
6 Summary of Results

After deriving the specific research questions in Section 3 and discussing the methods and data in Section 5, this section presents the main findings of the four papers contained in this thesis. For the sake of clarity, only the most important results of each of the papers will be discussed. For a more detailed, empirically grounded description of the findings, the interested reader is referred to the original papers in Annex I. The implications of the results for the literature, policy makers and corporate managers will be discussed in Section 7.


Table 3 shows the main findings of our comparative case study that investigated how deployment policies affect corporate investments in technological exploration and exploitation. As the most important result of our study, we find that policy-induced market growth does not have the same effect on all firms in the PV industry. Rather, the technological maturity of the product technology pursued by the respective firm emerged as an important moderating factor. Following Foxon (2005), we define technological maturity as the stage of a technology in the technology life-cycle. In the following we separately discuss the effect of deployment policies for firms pursuing more and less mature technologies in the PV industry. As described in Section 4, the former group comprises firms primarily pursuing wafer-based c-Si PV, whereas the latter consists of firms active in the field of thin-film or emerging PV technologies.

For firms pursuing more mature PV technologies, deployment policies create an incentive to invest in production capacity and sell products in the emerging market. The income the firms generate this way is used to finance investments in both R&D (i.e., exploration) and further increases in production capacity (i.e., exploitation). The managers we interviewed in the course of our case study underscored that revenues generated from policy-induced market growth represent an important income stream to finance exploration activities. In this sense, deployment policies will generally raise the level of exploration within firms pursuing more mature PV technologies (see upper left part of Table 3). At the same time, however, we find that the stronger the policy-induced market growth, the more firms will be inclined to raise their investments in production to a larger degree than their investments in R&D. In the PV industry, this is reflected in a negative correlation between market growth and R&D intensities. We find three major mechanisms that explain why high rates of policy-induced market growth induce firms to shift their balance between exploration and exploitation towards exploitation (see lower left part of Table 3). First, given a certain level of
supply, higher policy-induced demand leads to larger profit margins in an industry which reduces the immediate pressure on firms to engage in risky, long-term R&D. Second, in times of high market growth, firms may experience a bottleneck in scarce human resources, requiring them to shift personnel from R&D to production. Third, in the PV industry deployment policies have opened up markets for firms that supply specialized production equipment. The availability of off-the-shelf equipment has significantly facilitated production investments of firms and in some cases created a disincentive for firms producing the cells and modules to invest in own R&D.

Table 3: Mechanisms linking deployment policies and corporate investments in technological exploration and exploitation for firms pursuing more and less mature PV technologies

<table>
<thead>
<tr>
<th>Effect of policy-induced market growth on exploration</th>
<th>Firms pursuing more mature PV technologies</th>
<th>Firms pursuing less mature PV technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive income effect: “The renewable energy law is important. The profit margin allows us to invest in research.”</td>
<td>Increased investor interest: “If there had been no legislation [fostering deployment] in place, investor appetite would not have been there. That was key.”</td>
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</tbody>
</table>

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<thead>
<tr>
<th>Effect of policy-induced market growth on balance between exploration and exploitation</th>
<th>Firms pursuing more mature PV technologies</th>
<th>Firms pursuing less mature PV technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced exploration pressure: “There was no need for R&amp;D because the EBIT margin was at an attractive level.”</td>
<td>Lack of physically mature product or production equipment: “We are still a pre-commercial company, so every dollar we raise is all going into R&amp;D.”</td>
<td></td>
</tr>
<tr>
<td>Trade-off in use of scarce organizational resources: „Before 2009 we were busy growing. […] This might have led to the situation where R&amp;D was only second priority.”</td>
<td>Higher barrier to market entry due to lack of economies of scale: “Nowadays, it’s difficult to enter the market as a player with great R&amp;D since you have to reach 5 GW scale to be competitive.”</td>
<td></td>
</tr>
<tr>
<td>Availability of specialized manufacturing equipment: “[A] lot of development work has completely shifted to [equipment manufacturers]. Equipment is available off-the-shelf and we add to this incrementally.”</td>
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</tbody>
</table>

For firms pursuing less mature technologies, i.e., thin-film or emerging PV technologies, deployment policies are important as they raise investor interest in an industry (see upper right part of Table 3). Since for these firms venture capital constitutes an important source of funding, deployment policies are a critical enabler for investments in both R&D and production. Despite this effect, firms pursuing less mature technologies do not benefit from deployment policies to the same extent as those with more mature technologies (see lower right part of Table 3). Since firms pursuing less mature technologies often do not possess a physically mature product or production equipment they
are usually not in a position to directly benefit from policy-induced demand. This limited possibility of firms pursuing less mature technologies to benefit from exploitation puts them at a disadvantage compared to more mature technologies in times of policy-induced market growth. Since firms pursuing more mature technologies are able to reap the benefits of economies of scale and learning by doing, deployment policies widen the cost gap between more and less mature technologies and raise the barrier to market entry for the latter. In fact, several of the company representatives and experts we interviewed stressed that emerging technologies might be intrinsically superior to wafer-based c-Si PV technologies. However, the firms pursuing the latter technologies reported that under existing conditions they could not compete with wafer-based PV and deliberately targeted niche markets such as building integrated PV.

6.2 Paper II: The Role of Inter-Firm Knowledge Spillovers for Innovation in Environmental Technologies – Evidence from the Solar Photovoltaic Industry

The main results of paper II are shown in Table 4. As described in Section 5.2, the goal of paper II was to test four hypotheses pertaining to the role of knowledge spillovers for firm-level innovation in environmental technologies. Specifically, we were interested in whether innovation in PV cells is driven by knowledge spillovers from R&D of other firms in the industry (hypothesis 1a) and whether these spillovers play a more important role than knowledge developed by the firm itself (hypotheses 1b). Moreover, we tested whether spillovers are moderated by the firm’s prior knowledge and investments in production equipment (hypotheses 2a and 2b).

<table>
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<tr>
<th>No.</th>
<th>Hypothesis</th>
<th>Supported?</th>
</tr>
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<tbody>
<tr>
<td>H1 a)</td>
<td>Knowledge developed by other firms in an industry has a positive effect on innovation in a firm’s environmental technology.</td>
<td>Yes</td>
</tr>
<tr>
<td>H1 b)</td>
<td>Knowledge developed by other firms in an industry has a smaller marginal effect on innovation in a firm’s environmental technology than the knowledge developed by the firm itself.</td>
<td>No</td>
</tr>
<tr>
<td>H2 a)</td>
<td>The effect of knowledge developed by other firms in an industry on innovation in a firm’s environmental technology is positively moderated by the knowledge developed by the firm itself.</td>
<td>(Yes)</td>
</tr>
<tr>
<td>H2 b)</td>
<td>The effect of knowledge developed by other firms in an industry on innovation in a firm’s environmental technology is positively moderated by the firm’s investment in manufacturing equipment.</td>
<td>Yes</td>
</tr>
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</table>
Our model offers clear support for the hypothesis that knowledge developed by other firms in an industry has a positive effect on innovation in a firm’s environmental technology. The regression coefficient measuring the effect of other firms’ knowledge on the cost-to-performance ratio of a firm’s PV cells is negative and highly significant (p > 0.001). In contrast, our analysis does not provide supporting evidence for the assumption that the marginal effect of knowledge developed by other firms in an industry is smaller than the effect of the knowledge developed by the firm itself. We find the knowledge stock developed by a firm’s own investments in R&D to have no direct, significant effect on the cost-to-performance ratio of its products at all. Nevertheless, according to our findings, R&D investments by firms are important as they enable firms to reap the benefits of knowledge spillovers. In line with hypothesis 2a, we find (albeit weak) evidence that R&D investments in the PV industry positively moderate the effect of knowledge developed by other firms on firm-level innovation. Moreover, our analysis also lends support for hypothesis 2b by showing that firm investments in production equipment serve as a moderating factor between knowledge from other firms and a firm’s innovation in environmental technologies. The results obtained for hypotheses 1a, 1b and 2b are fairly robust against changes in the assumed knowledge depreciation rates and lags. The result for hypothesis 2a, however, becomes insignificant when assuming low depreciation and higher lags for the stock of knowledge of other firms as well as lower depreciation rates and lower lags for the stock of knowledge from public R&D.

The finding that knowledge developed from firm-internal R&D does not directly affect the cost-to-performance ratio of a firm’s PV cells can be explained by a) the small size of our sample, b) our focus on measuring innovation in wafer-based c-Si technologies which does not capture effects of R&D investments on advances in alternative technologies and c) the rapid growth of the PV industry and related knowledge which might induce firms to use R&D as a means for external knowledge acquisition rather than own development of knowledge. The finding that investments in manufacturing equipment positively moderate knowledge spillovers lends support for anecdotal evidence that the emergence standardized equipment has played an important role in driving changing leadership positions in the PV industry. As discussed in Section 4, there is first evidence in the literature that equipment manufacturers have integrated knowledge into their products that was developed in close collaboration with primarily Western manufacturers of PV cells. By exporting the equipment to China and Taiwan, producers of PV cells in these countries were able to tap this knowledge and produce PV cells at a high quality and low cost without having to make large investments in R&D.

As described in Section 5.3, paper III draws on a longitudinal case study of the German feed-in tariff system for solar PV to investigate how the complex dynamics of socio-technical systems shape the process of policy interventions targeted at inducing technological change. Our analysis shows that the German feed-in tariff system for solar PV has gone through a large number of legislative changes, each of which addressed specific issues in the socio-technical system. A key motivation for enacting the Renewable Energy Sources Act (EEG) in 2000 was to raise the financial incentive for installing PV plants, thereby enabling firms to enter the stage of mass production, reduce the costs of PV technology and create domestic jobs in a promising high-tech industry. However, over time, with increasing PV deployment and falling technology costs, a number of issues emerged that were not foreseen by policy makers. First, the number of PV installations increased much faster than expected, culminating in debates about the costs connected to technology support that had to be borne by electricity consumers. Second, costs of PV technology fell at a considerably higher rate than predicted and resulted in windfall profits for both producers and users of PV technology. Third, especially in recent years, increasing deployment of PV has raised concerns about the stability of distribution grids and the longer-term integration of renewable sources into the electricity market. Finally, while initially the German industry performed well, in recent years a strong Chinese industry has emerged which markets its products in Germany, thereby directly profiting from the demand-side subsidies put in place.

German policy makers reacted to each of these issues by implementing changes to the design of the feed-in tariff system. These changes were often successful in resolving the immediate bottleneck, e.g., reducing windfall profits, and can be considered crucial when trying to understand the effectiveness and continuity of the German feed-in tariff scheme. At the same time, however, our analysis shows that not only the solution of issues but also the emergence of new ones was closely related to policy interventions. When implementing a policy, policy makers addressed a set of prevalent issues in the socio-technical system. As illustrated in Figure 7, however, changes in policies rarely presented accurate answers to less immediate, future issues. On the one hand, this is due to the fact that the evolution of complex socio-technical systems is hard to foresee. On the other hand, however, policy interventions themselves often triggered changes in the socio-technical system that – through complex system interdependencies – led to the emergence of new issues. The more momentum the socio-technical system gained, the more unforeseen technological developments exerted direct pressures on policy makers to adjust the design of previously implemented policies. In this sense, technological change served as both an outcome and a driver of policies targeted at inducing technological progress. We argue that the general pattern of the resulting process is similar.
to what Rosenberg (1969), described as ‘compulsive sequences’ in the evolution of technical systems. We therefore label our framework ‘compulsive policy-making’.

6.4 Paper IV: The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems – A Review and a Scenario-Based Optimization Model

Paper IV used a techno-economic modeling approach to address the research question when and under which conditions battery storage will be economically viable in residential PV systems without demand-side subsidies for an economically optimized system configuration. Our model results show that investments in battery storage were already economically viable in 2011 under scenarios that assume stronger increases in future electricity retail prices for very small residential PV systems (see Figure 8). Without policy support in early years households invest in relatively small PV systems and storage to maximize self-consumption. However, with falling prices for PV and storage technologies, the optimal PV system and storage sizes rise significantly over time such
that between 2015 and 2018 households become net electricity producers if they are provided access to the electricity wholesale market.

The trend of rising profitability of storage and increasing sizes of both PV and storage systems is robust across all investigated scenarios. Still, the ideal configuration of the integrated PV-storage system is strongly dependent on the expected development of wholesale and retail electricity prices. As shown in Figure 8, the profitability of storage is generally higher under scenarios with high electricity retail prices as higher retail prices raise the benefit of consuming electricity generated by the PV system compared to purchasing electricity from the grid. As a result, under a scenario of high retail prices, households not only invest in larger PV plants but also larger storage systems than under a scenario with lower retail prices. Higher wholesale prices similarly raise the size of PV systems a household invests in since surplus electricity can be sold at higher prices on the market. At the same time, however, they have a dampening effect on the profitability of storage. Lower wholesale prices raise the profitability of storage especially in later years when PV systems are large and households tend to sell a higher share of their electricity to the market. Even when assuming that the household does not have access to the wholesale market at all, this does not reduce the
profitability of storage but, on the contrary, even raises it. Under the latter scenario, however, the optimal size of PV systems installed becomes very small such that in all scenarios the household produces less electricity than it consumes.
7 Conclusion

The objective of this thesis is to investigate the role of deployment policies in fostering innovation for clean energy technologies. The following section synthesizes the contributions this work makes to the literature. Subsequently, the most important implications for policy makers and managers are summarized. This thesis concludes by pointing to promising avenues for future research.

7.1 Contributions to the Literature

This work makes at least four contributions to the existing literature. First, this research provides a more nuanced perspective on the mechanism through which deployment policies induce technological innovation with important implications for their effect on technological diversity. As described in Section 2.1, there is a consensus in the literature that demand and deployment policies can induce innovation but that innovations driven by demand are more incremental than those resulting from supply-side factors (see Section 3.1). Our findings in paper I challenge and refine this perspective in several ways: We find that, contrary to the dominant view in the literature, deployment policies can serve as an important catalyst for innovation beyond existing technological trajectories by raising the funds available to be invested in R&D for both established firms and start-ups. Both equity- and debt-financed innovative activity in thin-film and emerging technologies has increased considerably with the burgeoning of policy-induced markets as investors and firms saw an increasing opportunity to market their innovations. At the same time, however, our findings clearly demonstrate that deployment policies do not equally benefit firms pursuing more and less mature PV technologies. Although deployment policies raise the absolute level of investments in novel technologies, firms pursuing these technologies are usually not in the position to benefit from market growth as much as firms with more mature technologies (see Section 6.1). Strong policy-induced market growth may thus raise the barrier to entry for less mature technologies and increase the risk of a technological lock-in. This finding is of large significance because in the literature deployment policies have usually been suggested as means to help resolving situations in which the development of novel technologies is hampered by existing technological regimes. Our results suggest that, while deployment policies may indeed be useful to fulfill this task and create niches for innovative technologies, they need to be designed with care to avoid reducing technological diversity and generate technological lock-ins within these niches.

Second, this dissertation sheds more light on the role and drivers of knowledge spillovers as a potentially important factor moderating the relationship between environmental innovation and the
competitive advantage of firms. The literature dealing with the Porter hypothesis and lead markets suggests that policy-induced innovation can raise the competitiveness of companies subject to policy support (see Section 2.1.1). By demonstrating that innovation in the PV industry is driven by knowledge spillovers in paper II, our results point to a potentially important contingency factor in the relationship between policy-induced innovation and firm-level competitive advantage. The idea that to generate a longer-term competitive advantage the resources underlying the strategies of firms need to be inimitable has long been stressed in the literature on the resource-based view of the firm (Barney, 1991, Wernerfelt, 1984). However, up to this point, the notion of spillovers and imitation has found little consideration in the literature on environmental innovation (see Section 3.2). Our study indicates that answering the question whether inducing environmental innovation leads to a competitive advantage requires an in-depth understanding of the channels through which firms in an industry absorb, dissipate and protect knowledge. We highlight investments in production equipment as one such channel which so far has received very limited attention in the literature on absorptive capacity. Currently, the literature predominantly assumes that to absorb knowledge firms need to invest in R&D. Yet, manufacturing equipment embodies significant knowledge gathered in the production of a good, allowing firms to integrate considerable amounts of knowledge in a relatively short period of time. Given that with increasing technological advancement and automation of production processes the availability of standardized manufacturing equipment can be assumed to play a more important role in a growing number of industries, we see much value in further investigating the role it plays as a channel of knowledge transfer.

Third, this work contributes to a better understanding of the dynamics that ensue when policy makers try to purposefully induce technological change. Paper III demonstrates that the design of deployment policies is influenced by developments in the technological realm. Due to the complexity of socio-technical systems, fostering technological change often leads to unforeseen side effects. The literature on technological innovation systems suggests that fostering the development and diffusion of technologies requires supporting a number of key processes or functions by removing so-called blocking mechanisms that hinder their execution. Our analysis demonstrates that policy interventions targeted at removing blocking mechanisms are much less trivial than is implicitly suggested in the literature on TIS. Contrary to the prevailing view in the literature on TIS, we show that interdependencies between functions need not necessarily be positive. Conversely, due to the complex dynamics of socio-technical systems, efforts targeted at removing mechanisms blocking one function may enhance existing or evoke new blocking mechanisms. The uncertainty surrounding the outcome of policy measures targeted at inducing technological change implies that to be effective, policy-making needs to be responsive to changes in the socio-technical realm. The
importance of flexible adaptation of policies and learning has been stressed in the literature on reflexive governance (Voß and Kemp, 2006). Since this literature puts strong emphasis on the inherently political, unpredictable and emergent nature of policy making, it has been rather separate from analytical approaches to policy making, such as the TIS framework. Our findings suggest that this current divide in the literature is unfortunate as both streams of literature hold major potential for informing each other. By describing the mechanisms through which analytical approaches translate into practical policy making processes, our framework of ‘compulsive policy making’ represents a first, humble step towards more closely integrating the work on TIS with the one on reflexive governance and policy learning.

Fourth, our study generates insights into the effects that deployment policies for a particular technology have on complementary technologies in the broader technical system. We show that the economic viability of battery storage for residential PV systems depends on the costs of both storage and PV technologies as well as electricity wholesale and retail prices. Deployment policies when implemented as feed-in tariffs lower investment costs for PV and simultaneously raise retail prices. As a result, although fostering investments in storage is generally not the main goal of policy making, deployment policies in the PV sector strongly contribute to raising the profitability of storage, thereby creating incentives for innovation not only in PV. Currently, the literature on deployment policies strongly focuses on evaluating the effects of policy instruments on the diffusion of technologies for which they set direct financial incentives. Our findings suggest that, especially for network and infrastructure technologies, such a perspective may be too narrow as it neglects positive (or negative) side effects of policy measures on complementary technologies. In this sense, the literature on technology and innovation policies could strongly benefit from a closer integration with the broader literature on technological systems (see Section 3.4) to study how policy interventions alter the configurations and links between system components.

7.2 Implications for Policy Makers

Besides making contributions to the existing literature, this work has important implications for practical policy-making. First, our results suggest that deployment policies are very effective means for inducing technological innovation. As described in Section 6.2, deployment policies raise investments in R&D for both established firms and start-ups. Moreover, they provide firms pursuing mature technologies with the opportunity to benefit from economies of scale, learning by doing and may lead to the emergence of specialized equipment suppliers. Especially the latter effects are hard to obtain when drawing on conventional, direct support of R&D, which is why deployment policies constitute an important complement to supply-side incentives. Still, our analysis shows that
these benefits of deployment policies go along with some inherent disadvantages. Whereas firms pursuing more mature technologies can benefit from policy-induced market growth, this is usually much less the case for firms pursuing less mature technologies as the latter often do not possess commercial products or the necessary production equipment to produce them. As a result, deployment policies raise the risk of a technological lock-in and reducing technological diversity within the industry they support. Such technological diversity, however, is important since future technological, economic, social and ecological developments are inherently unpredictable, requiring policy makers to take a portfolio approach (Stirling, 2010). For example, at present it still remains to be seen whether wafer-based c-Si PV technology can reach a cost level at which it can compete with conventional power sources such as coal (van den Heuvel and van den Bergh, 2009). In this context, given the lower material intensity and the highly automated production process, thin-film PV might constitute an interesting alternative to wafer-based PV in the future. We suggest three policy measures to reduce the adverse effect of deployment policies on technological diversity: As a first measure, policy makers may consider reducing market growth rates to give firms pursuing less mature technologies more time to engage in capital- and time-consuming technology development. This measure has the advantage of simultaneously reducing the annual amount of public spending but may be undesirable from an ecological perspective as it slows down the diffusion of clean energy technologies. As a second measure, policy makers can design deployment policies in a way that provides different incentives for technologies at different stages in the life cycle. By creating sub-niches for promising technologies, e.g., by providing higher feed-in tariffs for emerging PV technologies, policy makers may create a portfolio of technologies from which they can draw in the future. As a third measure, policy makers need to complement deployment policies with R&D and venture support. Currently, deployment policies are often seen as a substitute for supply-side policies, such as R&D subsidies or R&D tax credits. Our analysis shows that reducing supply-side incentives while supporting deployment may be a risky strategy if policy makers wish to avoid a premature lock-in into particular technologies.

As a second important implication, our findings suggest that, while deployment policies are well suited to induce technological innovation, this does not necessarily imply that they generate a competitive advantage for firms located in the country in which the policy is introduced. The

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*Note that the risk of generating a lock-in is not limited to deployment policies that target specific industries or technologies, such as feed-in tariffs for solar power. Instruments such as emission trading systems or a carbon tax also predominantly benefit more mature technologies within the sector which they regulate. For example, introducing a policy that requires all European utilities to participate in a cap-and-trade carbon market induces demand particularly for those low-carbon energy technologies that at the time of introducing the policy have low carbon abatement costs, e.g., wind. As a result of the policy-induced demand, wind energy firms will have more resources to invest in advancing the technology compared to other technologies that are further from commercialization (e.g., PV). In this sense, as noted by Azar and Sandén (2011), policy interventions are never ‘technology neutral’. Instead, they involve a political choice between leveraging existing technologies (for reasons of economic efficiency and lower social costs in the present) and investing in technological alternatives (to build a portfolio of promising technologies that may outperform present ones in the future).*
question whether deployment policies can serve as industry policy depends on the presence of knowledge spillovers. Knowledge spillovers raise the effectiveness of policy interventions targeted at inducing technological innovation as they make technological knowledge available to a larger number of firms. Consequently, knowledge spillovers are in fact desirable from a societal perspective. At the same time, however, knowledge spillovers reduce the possibility of domestic firms to appropriate the benefits from innovation. Therefore, policy makers interested in generating a domestic competitive advantage may consider taking measures that reduce knowledge spillovers to foreign firms. To achieve this goal, policy makers could encourage firms to invest more strongly in their protection of intellectual property. Yet, by reducing the possibility of domestic firms to build upon each other’s knowledge, this measure bears the risk of significantly hampering innovation in the country itself. As an alternative, policy makers should consider supporting industries that more strongly rely on tacit knowledge. Since spillovers in such industries tend to be more locally bounded, inducing innovation is likely to spur industrial competitiveness to a larger extent than in industries with a high degree of codified knowledge.

Third, as pointed out in Section 6.3, deployment policies need to be designed in a way that enables policy makers to react to and learn from unforeseen outcomes of policy interventions. The case of the German feed-in tariff system shows that every change in the detailed design of legislations can trigger unexpected dynamics. As a result, a frequent monitoring of developments and revision of policy is a critical ingredient of efficient deployment policies. In fact, the high effectiveness and continuity of the German feed-in tariff for solar PV can be largely attributed to the inclusion of formal feedback and adjustment mechanisms. From the beginning, policy makers were aware that the law would have to be revised. Therefore, already in the first version of the EEG 2000, they implemented a revision cycle that was based on expert consultations, frequent interpellations and experience reports prepared by external authorities. This institutionalization of learning on the side of policy makers allowed flexibly adapting the feed-in tariff system to unforeseen issues, thereby strongly contributing to its success. Future deployment policies should thus be designed in a way that enables policy learning and adaptation. To avoid uncertainties that may result from excessive policy changes, however, it is of major importance that revisions of policies occur in a transparent and predictable way. In this context, a comparison of the German case with developments in other countries, such as Spain, suggests that continuous monitoring and scheduled, incremental modifications to the policy are likely to give better results than infrequent, large-scale policy changes.

Finally, our findings show the importance of considering complementary technologies when designing deployment policies. As discussed in Section 6.4, rising retail prices, falling wholesale prices and lower investment costs of PV contribute to an increasing economic viability of storage
for residential PV systems. Interestingly, in the past all three effects are closely tied to the use of deployment policies for PV technology. As a result, **deployment policies themselves have contributed to an increasing economic viability of storage technologies**. Yet, although households face an increasing economic incentive to install battery storage, this does not necessarily imply that this is also desirable from a societal perspective. Currently, it remains controversially debated whether implementing small-scale, distributed storage can significantly reduce the throughput and required capacity of the electricity grid (Büdenbender et al., 2010). While some authors find small-scale battery storage to reduce the burden on distribution grids (Hollinger et al., 2013), others argue that small-scale storage may even add to instabilities since electricity feed-in patterns of distributed electricity generation could become less predictable (Sauer et al., 2011). As a result, policy makers need to closely observe the effect of deployment policies on complementary technologies. In case that private and public incentives diverge, i.e., complementary technologies are not deployed at a sufficient rate or scale, additional policy measures might have to be introduced that alter the configuration of the broader technical system.

### 7.3 Implications for Corporate Managers

Deployment policies can have major effects on firms operating in markets directly or indirectly driven by political incentives. Therefore, in the following, four lessons shall be pointed out that managers can learn from the analysis presented in this thesis.

As described in Section 6.1, policy-induced market growth allows firms to generate revenues and raises the interest of investors in the industry. As a result, deployment policies represent an important means for increasing the financial resources available to firms which can be invested in both production and R&D. Managers that recognize the opportunities and develop marketable products in a timely manner can reap considerable benefits from policy-induced markets. Firms pursuing more mature technologies can scale up their production to benefit from economies of scale, learning by doing and enhanced income streams. Firms pursuing less mature technologies can leverage the existence of policy-induced market growth as an argument when trying to secure financing. However, as markets grow and product costs in the industry fall, entry for novel technologies may become more and more difficult. Therefore, **with the emergence of deployment policies speed of technology development and production ramp-up become critical** for start-ups pursuing novel technologies. To not miss the window of opportunity and be left behind in the race for market share, managers should closely monitor the development of deployment policies in the most important markets. While forecasting the exact growth rates of policy-induced markets has proven extremely difficult, **a good understanding of the key drivers and dynamics seems
indispensable for firms operating in markets driven by deployment policies. Among other things, this requires a profound understanding of the political landscape, the policy schemes in place and under development as well as the broader socio-technical context. Retrospective policy analyses and prospective techno-economic models, such as the ones developed in paper III and IV, can be of great help in this process as they help managers to identify possible scenarios and develop strategies to cope with potential developments.

While developing the capabilities and technologies for exploitation become critical success factors in the presence of deployment policies, this thesis presents evidence that firms may tend towards putting too much emphasis on exploitation to the detriment of exploration during time of strong market growth (see Section 6.1). We show that, especially in terms of human resources, firms face a trade-off between exploration and exploitation. In times of strong market growth, opportunity costs for longer-term R&D are particularly high and qualified personnel is limited which induces firms to shift personnel from explorative toward exploitative activities. While this strategy may seem reasonable in the short-term, we present some evidence that it may be risky from a longer-term perspective. As paper II shows, investments in R&D are important to absorb knowledge from other firms in an industry. Especially during times when an industry – and with it the related technological knowledge – is growing at a fast pace, it is therefore of major importance for firms to continuously raise investments in R&D. Actively managing the trade-off between exploration and exploitation is one of the main tasks of managers – especially during periods of strong market growth – and is likely to play a critical role for firm survival in the longer run.

Besides pointing to the importance of actively managing investments in production and R&D, our findings imply that managers trying to build a competitive advantage for their firms need to think strategically about knowledge spillovers. The literature on ‘open innovation’ stresses the opportunities for firms that ensue when they engage in research collaborations to internalize external knowledge. The example of the PV industry shows that, while often useful, such collaborations also bear great risks. In paper II we provide empirical evidence that knowledge spillovers in the PV industry have been driven by investments in production equipment. This equipment was often developed in close collaboration between PV manufacturers and equipment producers. Since the former did not sufficiently protect the intellectual property, equipment producers were able to sell machinery that embodied the collaboratively developed knowledge, thereby undermining the competitive advantage of their former partners. To avoid making similar mistakes, managers should pay close attention to potential channels through which knowledge can flow out of their firm. Not only needs knowledge be protected through patenting, but it should also play an important role when developing the firm’s strategy with regard to alliances and technologies to be pursued. For example, at least part of the firm’s technology portfolio should consist of
technologies for which a firm possesses unique knowledge, making the firm’s strategy hard to imitate by competitors.

Finally, paper IV demonstrates that consequences of deployment policies can often go far beyond fostering the diffusion of a single technology. Especially in sectors in which multiple technologies and actors are closely interlinked to generate value for a customer, deployment policies have the potential to fundamentally alter the entire industry structure. Already now in a rising number of countries, policy-induced deployment of renewable energy technologies has material effects on the balance sheets of electricity producers and technology providers. Electricity producers are confronted with households that in recent years have started to move from being loyal customers purchasing electricity to being competitors producing and selling their own electricity. Simultaneously, due to the rise of deployment policies, in some countries, such as Germany, investments in conventional fossil fuel-based power plants has strongly decreased since, with power of renewables being fed into the grid preferentially, fossil fuel plants cannot be operated at maximum capacity. These trends fundamentally undermine the existing business models of both utilities and the firms developing and producing technologies for conventional power generation, such as coal-fired power plants. Monitoring deployment policies therefore is not only in the interest of those directly benefiting from the financial incentives put in place. Rather, understanding the dynamics and effects of deployment policies is of utmost importance also for managers producing and using those technologies competing with or complementing the ones benefiting from policy support.

7.4 Future Research

This thesis contributes to a better understanding of the role that deployment policies play in fostering technological innovation. However, as any research project, this thesis is limited in the ground it can cover. In the following, three promising avenues are outlined along which future research can help extending the findings presented in this work.

First, the analysis in this thesis is confined to the solar photovoltaic industry. Given the strong dependence of this sector on policy support, PV is well suited as a case for studying the dynamics and effects of deployment policies (see Section 4). Nevertheless, an important question to ask is to which degree the findings presented are generalizable to other technologies and sectors. Existing research suggests that many of the general patterns outlined in this thesis may in fact be similar for other clean energy technologies. For example, Karnøe (1990), Garud and Karnøe (2003) and Nemet (2009) provide evidence that, similar to our findings in paper I, deployment policies may have
induced firms in the wind industry to shift their focus from exploration towards exploitation. Similar to the developments in the PV industry, production of wind turbines has gradually – although less rapidly – shifted from European and American to Chinese companies, raising the question which role knowledge spillovers might have played (Zhang et al., 2013). Deployment policy schemes for wind power have dynamically evolved in response to developments in the socio-technical realm (e.g., Szarka, 2006). Moreover, like solar power, the diffusion of wind power has given rise to increasing investments in complementary technology, such as grid technology (Lund, 2005). Therefore, while in sum many of the findings in this thesis seem applicable to other sectors, the detailed effects of deployment policies are likely to depend on the specific characteristics of the different clean energy technologies (Huenteler et al., 2012). Compared to other technologies, PV technology is highly modular and commoditized. It seems reasonable to assume that the patterns of innovation processes for technologies that do not possess these characteristics look different from the ones of PV. Innovation patterns, in turn, are closely linked to industry structure (e.g., dominance of small or large firms), the drivers of competitive advantage (e.g., focus on costs or performance) and the channels of knowledge spillovers (e.g., turnover of personnel vs. investments in production equipment). In sum, therefore, future research seems necessary that investigates how the dynamics and outcomes of deployment policies differ between technologies.

Second, it is recommended that future studies explore to which extent the effects of deployment policies on innovation differ for different deployment policy instruments. As described in Section 1.2, deployment policies can take various forms, reaching from low-interest loans and renewable portfolio standards to feed-in tariffs. Although some instruments, such as feed-in tariffs, have found particularly wide spread use, countries still differ considerably with regard to the instruments they use. Future research should therefore investigate to which extent the different instruments complement or substitute each other with regard to their effect on both diffusion and innovation. Moreover, an interesting question to be addressed in future research is how the different instruments themselves have diffused over time. Paper III suggests that the use of particular instruments in countries may be closely related to the particular problem a country has faced in the time of its introduction. Low-interest loans, for example, might be the instrument of choice if the bottleneck lies in an insufficient access of users to capital. Beyond this explanation, however, there is some evidence that institutional factors could have played a substantial role in instrument choice. Countries which have traditionally favored free-market approaches seem to have made use of deployment policy instruments which are of a less interventionist nature. Whereas many European countries have focused on feed-in tariffs, the majority of US states have favored renewable portfolio standards. The latter provide little incentive for private households to invest in distributed power generation, thereby leaving the industry structure of the electricity sector largely unchanged.
Moreover, in our interviews we found evidence that policy makers in countries with policy schemes in place have actively engaged in promoting their exports to other countries, thereby acting as ‘institutional entrepreneurs’ (Maguire et al., 2004). In this process, besides the goal of fostering the global deployment of renewables, intentions to support exports of domestically produced technology seem to have played important roles. Yet, to provide a detailed account of the drivers of policy diffusion, future research seems necessary that systematically investigates the reasons for introducing the different deployment policy instruments in different countries.

Third, this work should be extended to investigate the effect of deployment policies on firms and organizations in the electricity sector other than those covered in this thesis. In order to provide a fine-grained perspective, the main focus of this work is on examining innovation among technology producers in the PV industry. As pointed out in the previous sections, however, the effect of deployment policies for PV goes far beyond incentivizing innovation among producers of PV cells and modules. Due to its modular nature, an increasing diffusion of PV has the potential to fundamentally change existing paradigms in the electricity sector. Instead of being powered by large-scale plants that are operated at high variable costs, the electricity supply of the future might be highly distributed with households producing their own electricity. The fact that the ‘fuel’ of solar power, solar irradiation is a free and public good implies that producers of PV power can enter the electricity market at zero marginal costs. As a consequence, already now it becomes visible that electricity market schemes which are based on variable costs will have to be revised to integrate renewable technologies. Given all these challenges that deployment policies and the related diffusion of clean energy technologies present to the status quo, it is interesting to investigate how established players respond to these changes. How do electric utilities, that have decades of experience in operating large, centralized power plants, perceive the emergence of distributed power generation? How do they adjust their business models to accommodate the threat of losing market share to private households? And what is the role of producers of conventional power technologies, such as components of coal-fired power plants? Should they adjust their technology portfolio to enter emerging markets for renewable technologies? And if so, when? All of these questions represent fruitful avenues for future research that have the potential to provide both interesting theoretical insights and important implications for policy makers and corporate managers interested in shaping the future development of the electricity sector.
8 Overview of Papers

The four papers included in Annex I are shown in Table 5 including the target journal and their current status in the review process. All of the papers are first-authored by the author of this thesis. The submission status of the papers is as of February 19, 2013.

Table 5: Overview of the papers included in the dissertation

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Annex I: Papers
The Two Faces of Market Support –
How Deployment Policies Affect Technological Exploration
and Exploitation in the Solar Photovoltaic Industry

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Abstract

The recent years have seen a strong rise in policies aiming to increase the diffusion of clean energy technologies. While there is general agreement that such deployment policies have been very effective in bringing technologies to the market, it is less understood how these policies affect technological innovation. To shed more light on this important question, we conducted comparative case studies with a global sample of 9 firms producing solar photovoltaic (PV) modules, complemented by in-depth interviews with 16 leading PV industry experts. We propose that, on the one hand, policy-induced market growth serves as an important catalyst for innovative activity as it raises the absolute level of firm investments in technological exploration. On the other hand, however, deployment policies create an incentive for firms pursuing more mature technologies to shift their balance between exploitation and exploration towards exploitation. Firms focusing on less mature technologies cannot tap the potentials of exploitative learning to the same extent as those with more mature technologies. Therefore, stimulating strong market growth may raise the barrier to market entry for less mature technologies. We conclude that, when designing deployment policies, great care should be taken to avoid adverse effects on technological diversity and a premature lock-in into more established technologies.

Keywords: Deployment Policy, Technological Innovation, Exploration, Exploitation, Solar Photovoltaic, Technological Lock-in
1 Introduction

Reconciling economic objectives with environmental concerns requires decoupling economic growth from its negative consequences such as resource depletion or the emission of greenhouse gases. A major lever to achieve this goal is the use of clean energy technologies. However, currently, many of these technologies are still at an early stage of development and not yet cost competitive with long-established fossil fuel-based energy technologies (IEA, 2011). Therefore, a question of significant importance is how public policies can foster technological progress in the field of clean energy technologies (e.g., Mowery et al., 2010).

While until the year 2000 government support largely focused on the direct funding of research and development (R&D), during the last ten years there has been an increasing focus on so-called deployment policies, targeted at diffusing clean energy technologies into the market. For example, to date more than 60 countries worldwide have introduced feed-in tariffs which grant producers of clean power a fixed price per unit of electricity (REN21, 2011). In a rising number of countries, the funding dedicated to deployment policies by far exceeds direct political incentives for R&D – for example, by a factor of around 40 in Germany (50hertz et al., 2010, BMU, 2010).

The literature on environmental policy suggests that, besides having a positive effect on diffusion, deployment policies can ‘induce’ innovation (e.g., Del Río González, 2009, Porter and van der Linde, 1995). Furthermore, quasi-evolutionary approaches to innovation policy recommend that regulators make use of deployment policies to create niche markets for technologies. Such niches are assumed to foster innovation in emerging technologies by shielding them from competition with established regimes (e.g., Kemp et al., 1998). However, up to this point the empirical literature provides only limited insights into the detailed mechanisms through which deployment policies affect innovation on an actor level. Studies in environmental economics generally investigate the innovation effect of deployment policies on a rather aggregate level of analysis, e.g., the sector (Cleff and Rennings, 1999). Empirical evolutionary research on deployment policies usually assumes a systems perspective without explicitly focusing on how these policies influence specific actors, such as firms, in their decisions to invest in innovative activities (Nill and Kemp, 2009).

A recent study by Nemet (2009) underscores the importance of analyzing the innovation effects of deployment policies on a more disaggregated level. Studying patenting activity in the wind industry, Nemet suggests that policy-induced market growth may have incentivized technology producers to ‘exploit’ existing products to benefit from learning-by-doing and economies of scale, while simultaneously setting a disincentive to ‘explore’ alternative technological options. A strong focus on technological exploitation relative to exploration, in turn, is likely to yield less radical
innovations and might raise the likelihood of technological lock-ins (Malerba, 2009, Sandén, 2005). Given that it remains unclear whether existing technological trajectories are sufficient to meet future economic, social and ecological goals, it seems advisable to avoid a premature lock-in into particular technologies (Stirling, 2010). Therefore, analyzing the detailed mechanisms through which deployment policies affect technological exploitation and exploration on the firm level could bear important implications for theory and praxis. Although the literature on organizational learning has identified various antecedents of firm-level exploration/exploitation, such as a firm’s slack resources, thus far there are no empirical studies available that investigate the impact of public policy (Lavie et al., 2010).

With this paper, we contribute to a more nuanced picture of how deployment policies induce innovation. In contrast to previous studies, we choose the firm as the unit of analysis and present systematic empirical data that describe how deployment policies affect corporate investments in technological exploration and exploitation. Following an inductive approach, we derive testable propositions, which are based on findings from in-depth interviews with 24 corporate managers in 9 European, US, Chinese and Japanese firms producing solar photovoltaic (PV) modules. These case studies are complemented by interviews with 16 leading PV industry experts. Besides providing a rich description of the mechanisms at work, our approach allows us to examine how deployment policies affect technological competition between more and less mature PV technologies.

The remainder of this paper is structured as follows: Section 2 provides an overview of past studies dealing with the innovation effect of deployment policies as well as the literature on exploitation and exploration. Furthermore, the initial theory framework as developed at the outset of the study is presented. Sections 3 and 4 introduce the research case and method. The results of our study are presented in Section 5, followed by a discussion of implications for theory and policy makers (Section 6). The paper concludes with a description of limitations, suggestions for future research and a brief summary of the main results.

2 Literature Review

2.1 Deployment Policies and their Effect on Technological Innovation

The notion that demand-side regulation can serve as an important driver of technological innovation has been discussed in two separate streams of research: the literature on environmental policy and quasi-evolutionary approaches to innovation policy.
The literature on environmental policy argues that environmentally benign innovation suffers from a so-called ‘double externality problem’ since the environmental side-effects of economic activity are not sufficiently reflected in market prices and, in the face of knowledge spillovers, firms may systematically underinvest in innovation (Rennings, 2000, Jaffe et al., 2005). In order to correct for these market failures, environmental policy scholars suggest that policy makers introduce regulatory measures to foster the adoption of environmental technologies and enhance innovation (Horbach, 2008). In this context, scholars have invested considerable effort in evaluating different instruments that directly or indirectly affect technology deployment, such as technology standards, tradable permits or feed-in tariffs (Jaffe et al., 2002, Jänicke and Lindemann, 2010). Although studies show a remarkable degree of ambiguity in their assessment of the individual instruments, there is a widespread consensus that demand triggered by deployment policies induces innovation (Newell et al., 1999). These findings are in line with the ‘weak version’ of the so-called Porter Hypothesis, which suggests that “properly designed environmental standards can trigger innovation” (Porter and van der Linde, 1995, p.98). Contradicting conventional neo-classical wisdom, Porter and van der Linde (1995) argue that environmental regulation may enhance innovation by signaling companies about resource inefficiencies and reducing investment uncertainties.

In quasi-evolutionary approaches, deployment policies are not only seen as a means to correct for externalities or managerial information deficiencies in an otherwise efficient market (Metcalfe, 1994, Nill and Kemp, 2009). It is reasoned that, more generally, policy makers can foster technological learning and may help to break technological lock-ins (Malerba, 2009). Technological lock-ins emerge as a result of a variety of factors, such as increasing returns to scale, network effects or industry standards (Arthur, 1989, David, 1985). While, on the positive side, these factors contribute to system stability and efficiency, technological search under a lock-in situation becomes highly localized and incremental in nature (Unruh, 2000). Since this precludes the development and diffusion of radically different, economically or ecologically superior technological alternatives, deployment policies have been recommended to create niche markets for environmental technologies where these technologies can advance without standing in direct competition with established technological regimes (Faber and Frenken, 2009, Kemp et al., 1998, Smith et al., 2005, Unruh, 2002).

While much progress has been made in describing and measuring the effects of deployment policies, the understanding of the exact mechanisms through which deployment policies induce innovation is much less well developed. Studies in the field of environmental economics often use highly aggregated measures of innovation, such as patents or R&D investments on the sector-level (Cleff and Rennings, 1999), and provide little insight into the firm-level dynamics linking deployment policies with the observed positive innovation effect (Ambec et al., 2011). Furthermore, work in the
field of environmental policy usually focuses on the firms directly affected by the regulation (e.g., for pollution control) rather than those supplying the required environmental technologies, for which deployment policies stimulate product sales and may create incentives for innovation (Schmidt et al., 2012). Quasi-evolutionary approaches to policy have a much stronger foundation in the micro processes of technical change. However, empirical studies usually take a systems perspective, not explicitly focusing on how policy may incentivize specific actors, such as firms, to invest in innovative activities (Nill and Kemp, 2009, Dosi and Marengo, 2007). Recent studies suggest that studying the link between deployment policies and technological innovation on a more disaggregated level, e.g., the firm level, may be critical since innovation can result from different modes of technological learning which may be differently triggered by deployment policies (Malerba, 2009, Hendry and Harborne, 2011).

2.2 Two Modes of Technological Learning: Exploration and Exploitation

March (1991, p. 71) suggests that, in general, firms can choose between two basic modes of learning: 1) Exploration, which he defines as “search, variation, risk-taking, experimentation, play, flexibility, discovery, and innovation”, and 2) exploitation which includes terms like “refinement, choice, production, efficiency, selection, implementation and execution”. He claims that, in order to survive in the longer term, organizations have to make use of both exploration and exploitation. At the same time, however, he points out that the two modes of learning constitute a trade-off as they compete for scarce organizational resources.

More recently, drawing on March’s framework, it has been proposed that the use of deployment policies in an industry may alter the balance between firm investments in exploration and exploitation. Nemet (2009) finds that deployment policies coincided with reduced patenting activity in the early phase of the US wind industry. As one of four potential explanations for his surprising finding, he suggests that deployment policies may have created a disincentive for the producers of wind turbines to invest in exploration as, in view of a rapidly growing market, they might have shifted their focus from exploration towards exploitation. Exploitation is likely to lead to more incremental innovations than exploration (Malerba, 2009). If deployment policies indeed discourage exploration, this implies that they might not be well suited to foster breakthrough innovations, a view that is backed by the classic literature on the drivers of technological change (see Mowery and Rosenberg, 1979, Schmookler, 1962). Freeman (1996, p.30), for example, points out that “the majority of innovation characterized as ‘demand led’ [...] were actually relatively minor innovations along established trajectories”. Moreover, a strong focus on exploitation may reduce technological diversity in an industry (Malerba, 2009) and could even contribute to the occurrence of
technological lock-ins. In fact, several authors have raised concerns that deployment policies in the PV industry might have encouraged a lock-in into more mature PV technologies as they allow firms pursuing these technologies to benefit from exploitative learning through learning-by-doing and economies of scale (Sandén, 2005, Menanteau, 2000, Sartorius, 2005, van den Heuvel and van den Bergh, 2009). Yet, at this point, it remains unclear how exactly deployment policies affect exploration and exploitation on an organizational level, leaving open whether deployment policies in fact induce only incremental innovation and enhance the risk of technological lock-ins.

2.3 Antecedents of Exploration and Exploitation

In the literature on organizational theory, considerable effort has been given to identifying factors that influence a firm’s propensity to invest in the two forms of learning relative to each other (Lavie et al., 2010, Raisch and Birkinshaw, 2008). It is argued that the balance between exploration and exploitation which organizations choose depends on industry-level antecedents such as environmental dynamism or competitive intensity (e.g., Levinthal and March, 1993, Jansen et al., 2006) and firm-internal factors such as firms’ slack resources (e.g., Greve, 2007, Nohria and Gulati, 1996) or their technology portfolio (Quintana-García and Benavides-Velasco, 2008). However, up to this point, there are no empirical studies that investigate the potential impact of public policy. Although it is acknowledged that “local governments may institute policies that influence organizations' predisposition toward either exploration or exploitation” (Lavie et al., 2010, p.145), it remains unclear how such policies influence the balance between exploration and exploitation chosen by an organization.

In sum, we argue that to advance our knowledge we require a more fine-grained approach that takes into account different modes of technological learning and examines the different channels through which these may be triggered by deployment policies. Since innovations, in the sense of novel commercial products, are usually created within firms, we suggest that there is particular value to be gained in studying the effect of deployment policies on the firm level. Firms differ fundamentally and systematically regarding their resources, capabilities and the technologies they pursue (Dosi, 1982). It therefore seems likely that firm and technology characteristics have an influence on how a particular firm chooses to innovate in response to a particular deployment policy (Del Río González, 2009, Kemp and Pontoglio, 2011).
2.4 Initial Theory Framework: Linking Deployment Policies with Firm-level Technological Learning

Figure 1 shows the preliminary research framework as derived from the literature at the outset of our study. Like previous studies on exploration and exploitation, we apply March’s framework to technological product innovation (e.g., He and Wong, 2004, Greve, 2007). Building upon March’s original definition, we define exploration as *all innovation activities pertaining to the generation of new technological options for the firm’s product portfolio*, whereas exploitation we define as *all innovation activities related to the execution of a firm’s existing product portfolio*. We assume that a firm’s level of exploration and exploitation is strongly related to the boundedly rational and discrete investment decisions of corporate managers. On the firm-level, the sum of these discrete choices shape a firm’s position on the exploration/exploitation continuum (Lavie et al., 2010). At the one extreme, a company may decide to solely focus on producing and selling existing products. This strategy is usually accompanied by benefits from learning-by-doing and economies of scale. At the other extreme, a firm may not produce and sell goods but invest in R&D to devise an entirely new product technology and reap the benefits of learning-by-searching. Following this logic, we generally regard corporate expenses for production capacity and manufacturing as investments in exploitation and expenses for R&D and demonstration as investments in exploration.\(^1\)

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\(^1\) In this study, radical innovations in process technologies are classified as exploration since these innovations are usually generated in R&D departments. Furthermore, they are closely connected to product innovation, as, for example, they often require or lead to drastic changes in product design. Incremental improvements of processes and up-scaling of production, however, are categorized as exploitation.
Regarding the construct of deployment policies, we assume that the main purpose of such policies is to create a market for technologies. Therefore, we focus on investigating the effect of policy-induced market growth, which we define as the _annual increase in market size induced by a deployment policy_. We are interested in the detailed mechanisms linking policy-induced market growth with investments in exploration and exploitation on an absolute level (1) and relative to each other (2). To account for the fact that firms are heterogeneous and pursue different technologies, we furthermore consider firm and technology characteristics which might moderate the effect of deployment policies on corporate investments in technological learning (3).

### 3 Research Case

As our research case we chose producers of solar photovoltaic (PV) modules. The PV sector is very well suited to investigating the effect of deployment policies on corporate investments in technological learning for two reasons. First, the market for PV modules is strongly dependent on deployment policies. Second, there are different PV technologies with distinct strengths and weaknesses and different stages in the technology life cycle, which justifies investments in both exploration and exploitation as potential avenues for technological advancement.

#### 3.1 The Role of Deployment Policies in the PV Sector

Although in recent years costs for PV technologies have fallen significantly, studies generally assume that photovoltaic power will not be fully cost competitive with conventional forms of electricity generation such as coal, gas or nuclear power before 2020 (Bagnall and Boreland, 2008). The fact that, despite the high costs, installed capacity of PV has escalated at an average annual rate of 57 percent since the end of 2004 (see Figure 2) points to the pivotal role of deployment policies (EPIA, 2011). Indeed, particularly since 2004, market support for PV has increased significantly with installed capacity, closely following the markets with the most attractive policy schemes (Taylor, 2008).

---

2 We limit our scope to companies producing photovoltaic modules as the main unit of analysis as – compared to firms producing system components such as inverters or mounting systems – these firms have a considerably higher share in the value added of photovoltaic systems (Peters et al., 2011). To ensure that the companies contribute significantly to the value-add of PV modules, we further required companies pursuing wafer-based crystalline silicon technologies (see Table 2) to have a vertical integration that spans at least the three value chain steps of wafer, cell and module.
Until 2004, mainly due to its sunshine program, Japan had been the biggest market for photovoltaic products (Watanabe et al., 2000, Algieri et al., 2011). In 2004, Germany amended its Renewable Energy Sources Act, resulting in a surge of domestic installed capacity by almost 300 percent compared to 2003. Although Germany does not offer favorable physical conditions for solar power, since 2004 it has consistently been one of the two largest markets for PV technology. In addition, during recent years an increasing number of countries have introduced deployment policies for PV, such as feed-in tariffs, renewable portfolio standards or tax incentives, leading to the emergence of new markets. Table 1 provides an overview of the seven most important markets for PV in 2010 with their respective deployment policy schemes. It shows that in 2010 market growth in each respective country was strongly linked to the attractiveness of the deployment policy schemes in place.

Figure 2: Development of PV markets 2004 to 2010 (data from EPIA, 2011)
Table 1: Overview of the most important PV markets and their deployment policy schemes in 2010 (data from EPIA, 2011)

<table>
<thead>
<tr>
<th>Country</th>
<th>Market Size 2010</th>
<th>Market Growth 2010</th>
<th>Deployment Policy Scheme 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>7,408 MW</td>
<td>94.6%</td>
<td>Feed-in tariff of up to 0.38 USD/kWh for rooftop, 0.32 USD/kWh for ground-mounted PV</td>
</tr>
<tr>
<td>Italy</td>
<td>2,321 MW</td>
<td>223.7%</td>
<td>Feed-in tariff of up to 0.64 USD/kWh for building integrated, 0.53 USD/kWh for ground-mounted PV</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>1,490 MW</td>
<td>274.3%</td>
<td>Feed-in tariff of up to 0.64 USD/kWh for rooftop and ground-mounted PV</td>
</tr>
<tr>
<td>Japan</td>
<td>900 MW</td>
<td>105.0%</td>
<td>Investment subsidy of 740 USD/kWc; feed-in tariff for surplus electricity of 0.55 USD/kWh for private households, 0.27 USD/kWh for commercial PV</td>
</tr>
<tr>
<td>United States</td>
<td>878 MW</td>
<td>84.1%</td>
<td>Federal investment subsidy of 30%; state-specific renewable portfolio standards, tax credits and net metering incentives; feed-in tariffs in Hawaii, Vermont, Maine, California, Washington and several municipalities</td>
</tr>
<tr>
<td>France</td>
<td>719 MW</td>
<td>228.3%</td>
<td>Feed-in tariff of up to 0.66 USD/kWh for building integrated, 0.53 USD/kWh for ground-mounted PV</td>
</tr>
<tr>
<td>China</td>
<td>520 MW</td>
<td>128.1%</td>
<td>Auctioning mechanism and investment subsidies on national level; feed-in tariffs in provinces of Zhejiang, Shandong and Jiangsu</td>
</tr>
<tr>
<td>Total (world)</td>
<td>16,629 MW</td>
<td>129.1%</td>
<td></td>
</tr>
</tbody>
</table>

3.2 Competing Technologies in the PV Sector

Currently, there are several PV technologies competing for market share that can be broadly divided into three groups: wafer-based crystalline silicon (c-Si), thin-film and emerging technologies (see Table 2). Among the three groups, wafer-based c-Si is the most mature technology which was first developed in the 1950s and used extensively in space applications before being considered for terrestrial purposes. Thin-film PV for larger-scale electricity generation has been around only since the mid-1970s and is in an earlier phase of the technology life-cycle than wafer-based c-Si. To produce c-Si modules, ingots made from crystalline silicon are cut into wafers, processed to solar cells and finally assembled to modules. Thin-film and emerging organic and dye-sensitized technologies, in contrast, are produced using a highly automated process during which a thin layer of semiconductor material is deposited on a carrier material, such as glass (Menanteau, 2000). While wafer-based modules generally have higher energy conversion efficiencies than thin-film, organic and dye-sensitized modules, they suffer from high material intensity and corresponding cost (Jacobsson et al., 2004, Bagnall and Boreland, 2008).
Table 2: Overview of PV technologies

<table>
<thead>
<tr>
<th>Category</th>
<th>Wafer-based Crystalline Silicon</th>
<th>Thin Film</th>
<th>Emerging Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technologies</td>
<td>mc-Si(^2), pc-Si(^3)</td>
<td>a-Si/µ-Si(^4), CIGS(^5), CdTe(^6)</td>
<td>CPV(^7), OPV(^8), dye-sensitized</td>
</tr>
<tr>
<td>Market Share 2010(^9)</td>
<td>86%</td>
<td>13%</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Technological Maturity</td>
<td>+</td>
<td>○</td>
<td>– (^9)</td>
</tr>
<tr>
<td>Material Intensity</td>
<td>–</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Conversion Efficiency</td>
<td>+</td>
<td>○</td>
<td>– (^{10})</td>
</tr>
</tbody>
</table>

\(^1\) Source: Photon (2012)
\(^2\) mc-Si: Mono-crystalline silicon
\(^3\) pc-Si: Poly-crystalline silicon
\(^4\) a-Si/µ-Si: Amorphous/micromorphous silicon
\(^5\) CIGS: Copper-indium-gallium-selenium
\(^6\) CdTe: Cadmium telluride
\(^7\) CPV: Concentrated photovoltaics
\(^8\) OPV: Organic photovoltaics
\(^9\) Except CPV (○)
\(^{10}\) Except CPV (+)

Since each technology possesses distinct strengths and weaknesses and bears significant potential for further improvements, it remains unclear which technology will deliver the best cost-to-performance ratio in the future (Sartorius, 2005, van den Heuvel and van den Bergh, 2009). Generally, for firms in the industry therefore both exploiting the potential of learning-by-doing and economies of scale within a particular technological trajectory as well as exploring alternative technological avenues seem valid options. Nevertheless, in the past some authors have raised concerns that the PV industry may in fact be locked into wafer-based c-Si technologies and pointed to a potential role of deployment policies (see Section 2.2).

4 Method and Sampling

To investigate our research question, we used qualitative case study research (Eisenhardt, 1989, Yin, 2009) for two main reasons. First, the link between deployment policies and investments in technological exploration and exploitation has not yet been explicitly addressed in previous research. The focus of the study therefore was on scrutinizing alternative causal mechanisms in order to build well-founded theory. According to Eisenhardt (1989) qualitative case studies are particularly well suited to fulfilling this task. Second, we chose case study research because this method allows for the studying of a phenomenon in greater depth than can be achieved using
quantitative methods. In using qualitative research we are able to discern alternative determinants of technological learning and provide a detailed description of the mechanisms at work.

For our analysis we proceeded in three major steps. First, to gain a profound understanding of the population of firms producing PV modules and the role of deployment policies, we conducted comprehensive desk research, drawing on publicly available data on the PV industry. For this purpose, we systematically scanned 163 annual reports of publicly listed producers of PV cells and modules published in the period from 1998 to 2010 (see Table A.1 in appendix) as well as all 131 issues of the leading PV industry magazine “Photon” from 1996 to 2009 for key words related to the main constructs of our research framework.3

As the second step of our research, to deepen our understanding of potential links between deployment policies and technological learning in the PV sector, we conducted a first round of interviews with designated industry experts. We chose leading experts with a broad range of different perspectives, such as policy makers, investors, project developers, scientists, market analysts, consultants and equipment manufacturers (Eisenhardt, 1989, Yin, 2009). The 16 experts we interviewed in the course of our research are shown in Table 3.

Third, building on the insights generated through the expert interviews, we interviewed a total of 24 representatives from 9 companies producing PV modules. Interviews with company representatives were considered the most direct way of generating insights into the mechanisms driving a firm’s balance between exploration and exploitation. We used theoretical sampling4 to identify companies a) located in different geographies and b) pursuing a wide range of PV technologies at different stages of development. Although policy-induced demand in the case of the PV industry has benefited both domestic and foreign companies in terms of sales and innovation (Algieri et al., 2011, Peters et al., 2012), location was considered an important sampling criterion to account for differences in national deployment policy instruments and a firm’s geographic proximity to high-growth markets. Furthermore, we chose to interview firm representatives in companies of different sizes pursuing a wide variety of different PV technologies to reveal potential influences of technology and firm characteristics, such as slack resources or technological maturity, on their reaction to policy incentives.


4 In contrast to ‘statistical sampling’ where a sample is selected randomly from a population, in ‘theoretical sampling’ cases are deliberately chosen in a way that allows to “replicate or extend emergent theory” (Eisenhardt, 1989, p.537).
### Table 3: Overview of expert sample

<table>
<thead>
<tr>
<th>Category</th>
<th>Person</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Policy Maker</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Member of German National Parliament</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Policy Analyst German Ministry of Environment</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Policy Analyst US Department of Energy</td>
<td></td>
</tr>
<tr>
<td><strong>Investor</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>PV Expert Venture Capitalist Clean Technologies</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>PV Expert Sustainable Investment Bank</td>
<td></td>
</tr>
<tr>
<td><strong>Project Developer</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Analyst Project Developer Renewable Energies</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Analyst Project Developer Renewable Energies</td>
<td></td>
</tr>
<tr>
<td><strong>Scientist in Public Research Institute</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Scientist Public Research Institute in Germany</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Scientist Public Research Institute in Switzerland</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Scientist Public Research Institute in the US</td>
<td></td>
</tr>
<tr>
<td><strong>Market Analyst/Consultant</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Analyst Market Research Institute</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Analyst Policy Consultancy</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Editor Industry Magazine</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Analyst Consumer Protection Agency</td>
<td></td>
</tr>
<tr>
<td><strong>Equipment Manufacturer</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Chief Executive Officer Equipment Manufacturer A</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Director Business Development Equipment Manufacturer B</td>
<td></td>
</tr>
</tbody>
</table>

Companies were contacted directly via postal mail. Since company representatives holding positions in general management, R&D, production, policy or strategic marketing departments were supposed to be best able to provide insights into our research question, we specifically approached managers in these functions. Moreover, since we were interested in motives for investments on the corporate level, it was considered important to interview at least one member of the company’s top management board. Our sample spans the entire spectrum of available PV technologies, from wafer-based crystalline silicon and thin-film to emerging technologies like organic and dye-sensitized PV (see Table 4). By interviewing company representatives from firms based in Europe, the United States, China and Japan, we were able to cover all major geographical regions that currently host producers of PV modules. Together, the firms in our sample have an accumulated world market share of around 15% which almost exclusively results from adding up the market shares of the five larger companies in our sample (firms A, C, E, F and I).
In our research design we followed the advice of Gibbert et al. (2008) to ensure a high level of internal, external and construct validity as well as reliability. To increase the internal and external validity of our framework and reduce potential biases resulting from impression management, company interviews during the third stage of our research were alternated with additional expert interviews (Eisenhardt and Graebner, 2007). Furthermore, whenever possible, we interviewed at least two company representatives per firm to enable triangulation of findings. Prior to all interviews we systematically scanned analyst reports, newspaper articles, annual reports and company statements for information related to our interviewee. These insights were translated into tailored interview guidelines which we then used as the basis for a semi-structured discussion during the interviews (see Table A.2 in the appendix for a typical interview guide). All interviews typically

For firms B, D, F and H it was considered appropriate to interview only one company representative since almost all firms were in an early start-up phase with little formal structures and the interviewee, typically the CEO, possessed a comprehensive knowledge of the company’s processes.

For a more detailed description of the technology categories see Table 2

Numbers indicate “persons in function interviewed/thereof members of executive board”
took between 45 to 90 minutes and were conducted by at least two researchers to ensure reliability of the findings. Interviews were recorded or independently documented by the interviewers in interview transcripts. These were later consolidated into a single document and saved in a central case study database.

Generally, during the interviews our period of interest regarding the effects of deployment policies on the PV sector was from 2004 to 2010. We chose this period of time because it accounts for more than 90 percent of today’s installed PV capacity and shows a strong prevalence of deployment policies.

To derive theoretical insights from the interviews, we applied analytical induction (Manning, 1982). After each interview, the members of the research team, of whom at least one had not been part of the interview, independently reviewed the interview transcripts and identified statements referring to the constructs of the research framework. For this step we made use of the qualitative data analysis software ATLAS.ti. We then applied pattern matching to identify relationships between the quotes labelled in the interview protocol corresponding to links between the constructs in our research framework (Yin, 2009). Whenever the analysis yielded obvious contradictions, we drew on secondary data to clarify the situation. Based on the insights gained through this process, we refined our constructs, developed testable propositions and integrated alternative explanations into our theoretical framework. The updated research framework, in turn, served as the basis for the following interview, a procedure which allowed us to continuously improve the internal and construct validity of our framework (Gibbert et al., 2008). Following the recommended procedure, we continued adding companies and experts to our sample until the additional theoretical insights gained during the interviews became small (Eisenhardt, 1989).

5 Results

In the following we discuss the detailed causal mechanisms through which deployment policies affect investments in technological exploration and exploitation of firms in the PV sector. We present our findings in three steps. First, we describe the effect of policy-induced market growth on firms’ absolute level of investments in technological exploration. We concentrate on explaining the link between deployment policies and exploration since the policy-related drivers for investments in exploitation in the PV industry – economies of scale, learning-by-doing and revenues – are rather perspicuous (see Section 2.2). The mechanisms we describe for the link between deployment policies and investments in exploration have, in parts, already been discussed in the more general literature.
on ‘demand as a driver of technical change’ and ‘new growth theory’. We nevertheless present them here to address the specific and open question whether deployment policies are generally suited to induce innovation beyond established technological trajectories or might – on the contrary – create a disincentive for investments in explorative learning. Second, we show how policy-induced market growth affects the firms’ balance between exploration and exploitation. Investigating differences in the effect for firms pursuing more and less mature PV technologies allows us to draw a nuanced picture of how deployment policies affect technology competition in the PV sector. Finally, to conclude the presentation of our results, we elaborate on a number of alternative factors which were assumed to affect firm-level investments in exploration and exploitation in the PV industry.

5.1 Effect of Policy-Induced Market Growth on Investments in Exploration

The interview results confirm our initial assumption that market growth in the PV sector is almost exclusively driven by deployment policies (see Table A.3 in appendix). But how does this policy-induced market growth affect corporate investments in exploration?

During the course of our study it became apparent that the mechanisms linking deployment policies and investments in firm-level technological learning strongly differ depending on the company’s product technology. In fact, the technological maturity of the firm’s products, which we operationalize as the stage of a technology in the technology life-cycle (Foxon et al., 2005), emerged as a particularly important moderating factor. To account for the fact that the mechanisms linking deployment policies and firm-level technological learning vary depending on this factor, in the following we separately discuss the mechanisms for firms pursuing more mature and less mature PV technologies. As shown in Tables 2 and 4, the former category comprises firms with a strong focus on wafer-based crystalline technologies (firms A, C, E, F, I). Compared to wafer-based technologies, thin-film and emerging PV technologies are less mature and pursued by firms B, D, G and H.

5.1.1 Firms pursuing more mature technologies

For firms pursuing more mature technologies, the main mechanism through which deployment policies affect investments in exploration is a positive income effect (see upper part of Table 5). In view of market growth, companies that possess commercial products are encouraged to exploit their existing product portfolio, expand their production and sell products on the market. The income they generate this way “is important [for companies] to be able to afford R&D” (Investor A). In fact, all company representatives of firms pursuing wafer-based crystalline PV technologies we interviewed stressed that “[t]he resources available for R&D are strongly linked to existing cash
flows” (Chief Technology Officer, Firm C) and that policy-induced market growth had been necessary to “reach a state where, at a certain level of revenues, there simply is a certain volume of R&D” (Market Analyst/Consultant B). These statements are in line with previous research which suggests that R&D investments increase with sales in an almost strictly proportional way (Hall, 1988). One reason for this phenomenon is that firms prefer equity over debt financing to fund risky R&D (Hall and Lerner, 2009, Rosenberg, 1990). As an important difference, however, demand in the case of deployment policies is exogenously triggered by policy makers, i.e., subject to political discretion (Hoffmann et al., 2008). Compared to ‘endogenous demand’, the dependence on public policy induces additional uncertainty about future income and the appropriability of investments which, for some companies, may dampen the positive effect of additional income on exploration (see Section 5.3 for a more detailed discussion).

5.1.2 Firms pursuing less mature technologies

Besides providing firms pursuing mature technologies with an income that can be invested in exploration, policy-induced market growth raises an industry’s capital resources through increased investor interest, an effect that is a critical driver of exploration among firms with less mature technologies (see lower part of Table 5). As Investor A pointed out “[t]here needs to be a market to arouse investor interest. A market consisting of four customers is too risky for a venture capitalist”. Consequently, as particularly younger companies pursuing thin-film and emerging PV technologies reported, market growth “was critical to attract venture capital” (Member of Board of Directors, Firm B). Venture capital support exists for all stages of start-up development and only “about 10 to 30 percent of venture capital” funding is used for pure R&D (Investor A). However, as has been pointed out in the literature on financing of innovation, venture capital is particularly effective in fostering exploration as “on average a dollar of venture capital appears to be three to four times more potent in stimulating patenting than a dollar of traditional corporate R&D” (Hall and Lerner, 2009, p.362). According to Scientist A “[i]n the 90s there was no interest of venture capital in PV, they just didn’t want to invest. [...] Then, the [German] Renewable Sources Act came and the whole scenario changed.” The market growth therefore set in motion a positive dynamic, drawing capital for exploration into the industry: “There’s an expression: When the sea rises, all boats rise, whether it’s a supertanker, a battle ship or a little inflatable dinghy. [...] Specifically, the more business, the more capital formation and movement, the more available capital for innovation, for example venture capital and grants from government. This primes the innovation pump. [...] So, it builds on itself. It’s like a snowball gathering mass as it rolls down the face of the Alps” (Chief Executive Officer, Firm G).
<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Exemplary Quote</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive income effect through exploitation</td>
<td>“The renewable energy law is important. The profit margin allows us to invest in research.”</td>
<td>Firm A, Chief Operating Officer</td>
</tr>
<tr>
<td></td>
<td>“Feed-in tariffs were so attractive that there was a lot of capital available. Companies had good cash flow which they could use to pursue different technological options.”</td>
<td>Firm C, Director Business Development</td>
</tr>
<tr>
<td></td>
<td>“In the period from 2004 to 2007 there was massive demand. By just jumping on the bandwagon you could spin as fast as the wheel. […] Many companies rely on grants. But you can’t be sure that you get them next year. When you generate revenue you can finance the research yourself.”</td>
<td>Firm E, President</td>
</tr>
<tr>
<td>Increased investor interest</td>
<td>“Investments in R&amp;D are also a question of financial resources. If there were enough resources available, we could easily employ 15 further researchers in R&amp;D and speed up the process. […] A bigger market leads to stronger investor interest and a higher availability of capital.”</td>
<td>Firm B, Chief Executive Officer</td>
</tr>
<tr>
<td></td>
<td>“[The market growth] was critical to generate VC interest. […] We went into the market at a time when the market was expanding. […] It was very important. I don’t think we would have raised a penny if we would have tried to raise money later. […] We were still a pre-commercial company, so every dollar we raised was all going into R&amp;D.”</td>
<td>Firm D, Member Board of Directors</td>
</tr>
<tr>
<td></td>
<td>“If there had been no legislation [fostering deployment] in place, investor appetite would not have been there. That was key.”</td>
<td>Firm E, President</td>
</tr>
<tr>
<td></td>
<td>“I think an impact that this rapid growth had was making venture capital people more enthused about the solar market in general and making equity investments that in essence funded R&amp;D of new technologies.”</td>
<td>Firm H, Chief Strategy Officer</td>
</tr>
</tbody>
</table>

In a nutshell, our findings do not offer support for Nemet’s (2009) suggestion that strong market growth reduces corporate investments in exploration. Instead, we find that policy-induced market growth raises the absolute level of exploration investments for firms pursuing both more and less mature technologies through higher revenues and elevated investor interest. We therefore phrase our first proposition:

**P I:** The higher the market growth induced by deployment policies, the more a firm will invest in exploration.
5.2 Effect of Policy-Induced Market Growth on the Balance between Investments in Exploration and Exploitation

The proposition presented in the previous section suggests that, on an absolute level, policy-induced market growth has a positive effect on investments in exploration. However, proposition I does not yet provide any insights on the balance between exploration and exploitation. In other words, it remains unclear whether – as also suggested by Nemet (2009) – with the emergence of deployment policies, companies increase their investments in exploitation to a larger extent than their investments in exploration.

5.2.1 Firms pursuing more mature technologies

Although R&D investments in the PV sector have continuously grown in absolute terms, the large majority of industry experts we interviewed reported that in recent years producers pursuing more mature technologies, such as wafer-based c-Si, had invested comparatively little into R&D relative to sales. For example, Policy Maker B expressed that “[i]t is a catastrophe that the [German] firms only have a R&D intensity of 2 percent. Why do they invest so little in R&D although they have earned good money?” In fact, as Figure 3 shows, the R&D intensity in the German PV industry has fallen quite significantly since 2001. As our interview partners asserted, this development cannot be attributed to a decline in technological opportunity. Project Developer B emphasized that the German PV industry itself had acknowledged that its current R&D intensity was too low, officially announcing their aim “to invest at least 5 percent of their revenues in R&D” in the future (see also Roland Berger and Prognos, 2010).

During our analysis we found that the phenomenon of declining R&D intensities is not limited to the German PV industry⁶ and may be closely linked to the strong market growth that has been triggered by deployment policy schemes. Before policy created mass markets for PV technologies, firms in the industry were “very much technology-driven, i.e., focused on basic research” (Chief Operating Officer, Firm C). “It was only through the growth in demand triggered by deployment policies” that companies were given the possibility to exploit their existing product portfolio and “make technological progress in the area of production processes, such as automation and higher throughput” (Investor B). Our results suggest that, although both exploration and exploitation investments rise with market growth, in times of higher market growth companies will raise their investments.

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⁶ The average R&D intensity of 25 global, publicly listed manufacturers of wafer-based crystalline PV cells, for which we could obtain data on R&D investments, was 1.54% (standard deviation of 1.49 percentage points) in 2010, compared to 5.06% (standard deviation of 10.06 percentage points) in 2005.
investments in exploitation by a higher percentage than their investments in exploration for three major reasons.\textsuperscript{7}

First, ceteris paribus, an increase in policy-induced market growth is accompanied by higher profit margins in the industry which results in reduced exploration pressure (see upper part of Table 6). As several of our interviewees reported, policy incentives for producing power from PV from 2004 until 2008 had been at such attractive levels that “profit margins were huge and customers snatched everything out of our hands that only barely looked like a photovoltaic wafer” (Firm A, Chief Operating Officer). As a result, companies were able to generate slack resources which lowered their immediate need to reduce product costs and engage in risky, explorative behavior. Illustrating this point in a very vivid way, an R&D manager at Firm A told us that “[u]ntil 2008 we lived in clover. The margins were high, innovation pressure nonexistent. […] We didn’t have a high R&D quota because there was no need for R&D.” The industry experts we interviewed

\textsuperscript{7} To provide first quantitative evidence for the proposition that policy-induced market growth may adversely affect R&D intensity of companies pursuing more mature technologies, we calculated the R&D intensities of 25 global, publicly listed manufacturers of wafer-based c-Si from 2004 to 2010 (N=164). Whereas R&D investments (in USD) are positively correlated with market growth (in GW and %), average R&D intensity (in %) is negatively correlated with both measures of market growth and lags from 0 to 2 (see Table A.4 in appendix). Note that these bivariate correlations, however, do not imply causality and that, probably due to the small number of time periods analyzed, only some correlations are statistically significant.
confirmed that “in the light of the generous support schemes, large efforts have never been necessary to serve the German market” (Market Analyst/Consultant D), “we have strongly growing markets which you didn’t have to develop using R&D” (Policy Maker A) and firms could “count on the fact that PV [modules] will be bought” (Scientist B).

Second, the higher the policy-induced market growth, the more firms pursuing more mature technologies will face a *trade-off in allocating their scarce organizational resources* to either exploration or exploitation (see middle part of Table 6). When operating in a market with stronger demand and higher margins, firms incur higher opportunity costs for organizational resources which they do not invest in exploitation “because the relative value loss of each unit of unsold product [is] so high” (Firm C, Chief Technology Officer). Interestingly, most of the companies we interviewed reported that there is no direct *financial* trade-off between investments in exploration and exploitation, as “R&D expenses are not remotely on the same scale as production capacity investments” (Firm C, Director Business Development). However, regarding *human resources*, the majority of interviewees confirmed that there is a clear trade-off between exploration and exploitation. Firms stressed that in terms of man-power in times of strong market growth “you are putting all your effort into volume increases” (Firm C, Director Business Development), “R&D was only second priority” (Firm A, Strategy Department) and “people working in technology development were drawn out of R&D and worked on building capacities” (Firm C, Chief Operating Officer). The fact that organizations shifted their human resources instead of hiring new personnel is due to the fact that there is a limit to the rate at which a department can grow “under quality considerations” (Chief Technology Officer, Firm C) and that “in high growth phases there is a constraint in talent” (President, Firm E). The shift in organizational focus towards exploitation translates into corresponding shifts on the monetary side (e.g., through reduced billings to the R&D department). Consequently, the trade-off in human resources is reflected in a focus of corporate financial investments in exploitation even though capital resources do not constitute the bottleneck.

Third, policy-induced market growth has led to the *availability of specialized manufacturing equipment* which has had a strong influence on the firms’ balance between exploration and exploitation (see lower part of Table 6). Firms supplying specialized equipment to the producers of PV modules “enormously profited from the strong demand for PV modules” and the associated strong rise in production capacity (Market Analyst/Consultant B). The availability of off-the-shelf equipment in turn has significantly facilitated exploitation strategies for firms pursuing more mature technologies, allowing for fast and easy upscaling of production. Simultaneously, the fact that equipment manufacturers conduct their own R&D which becomes “embodied in the next generation equipment” and is made “available to everyone” (Market Analyst/Consultant A) in some cases seems to have created a disincentive for PV producers to invest in exploration. Since
further developing existing or devising completely new technologies is a time-consuming endeavor, in the presence of strong spillovers, firms run the risk that they “invest in an R&D project, develop a new cell concept and just before we are done, we hear that there is new turn-key equipment available which produces a [PV] cell with a higher conversion efficiency” (Business Development, Firm A). Overall, therefore, our study provides evidence that policy-induced market growth raises the availability of specialized manufacturing equipment, which in turn creates an incentive for the firms producing PV modules to shift their balance between exploration and exploitation towards exploitation.

In summary, our findings concur with Nemet’s (2009) suggestion that deployment policies will alter firms’ balance between exploration and exploitation. More specifically, we find that for firms pursuing more mature technologies higher policy-induced market growth will reduce a firm’s exploration pressure, set strong incentives to use scarce human resources for exploitation and facilitate exploitation through the emergence of specialized manufacturing equipment. We therefore suggest the following proposition:

\[ P \text{ II: The higher the market growth induced by deployment policies, the more a firm pursuing more mature technologies will invest in exploitation relative to exploration.} \]

\[ * \text{While we find that in some cases equipment manufacturers have taken over exploration activities from producers of PV modules, our study does not provide evidence that deployment policies induce firms to systematically in- or outsource R&D activities from/to public research institutes. Furthermore, interviewees reported that equipment manufacturers themselves have shifted personnel from exploration towards exploitation in times of strong policy-induced market growth.} \]
Table 6: Mechanisms through which policy-induced market growth affects the balance between exploration and exploitation for companies pursuing more mature technologies

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Exemplary Quote</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced exploration pressure</td>
<td>“There was no need for R&amp;D because the EBIT margin was at an attractive level.”</td>
<td>Firm A, Business Development</td>
</tr>
<tr>
<td></td>
<td>“If incentive schemes had been a bit more modest, you would have had less focus on volume and more focus on longer-term technology developments.”</td>
<td>Firm C, Chief Technology Officer</td>
</tr>
<tr>
<td></td>
<td>“This [European] industry is inherently lazy. This is because the feed-in tariff structure until recently has been very generous. Only when forced, innovation and research really starts.”</td>
<td>Firm F, Vice President</td>
</tr>
<tr>
<td></td>
<td>“That the firms have not seen R&amp;D as a large lever could be due to the fact that, during the last few years, they could produce at much lower cost than had been assumed by policy makers which led to excess levels of policy support. Therefore, they might not have felt pressured to invest in R&amp;D. If I had a profit margin of 40 or 50 percent and had to make large investments [in R&amp;D] for the next 5 percent, I would ask myself whether these additional 5% are really worth the effort or whether I should stay at ‘only’ 40 to 50 percent.”</td>
<td>Project Developer A</td>
</tr>
<tr>
<td>Trade-off in use of scarce organizational resources</td>
<td>“Before 2009 we were busy growing. It was about satisfying customer needs in a fast growing seller’s market. This might have led to the situation where R&amp;D was only second priority.”</td>
<td>Firm A, Strategy Department</td>
</tr>
<tr>
<td></td>
<td>“High growth leads to a focus on production. There is always a lot of development going on in production. What happened is that many people working in technology development were drawn out of R&amp;D and worked on building capacities.”</td>
<td>Firm C, Chief Operating Officer</td>
</tr>
<tr>
<td></td>
<td>“In the years of high market growth you lose focus on longer-term R&amp;D.”</td>
<td>Firm C, Chief Technology Officer</td>
</tr>
<tr>
<td></td>
<td>“If we were a [pure] PV company, you could see that ramping up production would be quite a struggle and R&amp;D might be impacted by that. But we are big enough and have a broad enough portfolio to handle that.”</td>
<td>Firm I, Director Research and Development</td>
</tr>
<tr>
<td></td>
<td>“The PV industry in Germany – particularly the technology producers – has simply neglected the issue of research and development. The companies were busy growing and earning money. […] They didn’t realize that the technology needs to be developed further.”</td>
<td>Equipment Manufacturer A</td>
</tr>
<tr>
<td>Availability of specialized manufacturing equipment</td>
<td>“The market growth explains the availability of turn-key equipment.”</td>
<td>Market Analyst/Consultant A</td>
</tr>
<tr>
<td></td>
<td>“During the Californian Gold Rush 1848, not the gold diggers have become rich but those selling the shovels.”</td>
<td>Scientist in Public Research Institute A</td>
</tr>
<tr>
<td></td>
<td>“Why do companies focus on more mature technologies? I would say it is mainly because of those firms that supply the production equipment. There has been quite significant progress on this side during the last years to increase the speed and efficiency.”</td>
<td>Firm E, President</td>
</tr>
<tr>
<td></td>
<td>“A few years back, producers needed to work closely with equipment suppliers. Now, a lot of development work has completely shifted to them. Equipment is available off-the-shelf and we add to this incrementally.”</td>
<td>Firm C, Director Business Development</td>
</tr>
</tbody>
</table>
5.2.2 Firms pursuing less mature technologies

In principle, firms pursuing less mature technologies face the same incentives to invest in exploitation during times of strong policy-induced market growth as those with more mature technologies. However, our interview results suggest that the former are usually not in a position to focus on exploitation to the same extent.

First, firms pursuing less mature technologies often have a strong focus on explorative activities because they lack a physically mature product or the necessary manufacturing equipment to produce at commercial scale (see upper part of Table 7). Therefore, these companies are usually “not commercially ready to capitalize on [...] booms” by selling their products in policy-induced markets (Chief Strategy Officer, Firm H). As Market Analyst C stressed deployment policies such as the German EEG “will automatically pull the one to the front which achieves commercialization at an earlier point in time [...]”

Second, during our interviews we found strong indications that for less mature technologies policy-induced market growth may even raise the barrier to market entry due to a lack of economies of scale, thereby further reducing their capacity to benefit from exploitation (see lower part of Table 7). Firms in the industry that exploit mature technologies can reap benefits of learning-by-doing and economies of scale which lowers the average product costs in the sector. As a result, “the dramatic growth in the crystalline, traditional PV market, driven by feed-in tariffs and other government incentives, has made the bar for entry into the market with new technologies higher, the window of opportunity narrower because with scale come down cost, with lower cost and better cost performance the threshold to introduce a new technology becomes higher and higher” (Chief Executive Officer, Firm G). To close the cost gap, companies pursuing less mature technologies have to either increase their investment in explorative learning to improve their product or invest in ever higher levels of production capacity. As a venture capital investor we interviewed reported, with increasing market growth “[t]he checks you have to write to finance capacity expansions are becoming very large. Today, you often need more than 100 million Euros” (Investor A). However, “the majority of VC funds manage a volume of 100 to 200 million Euros” of which a “typical venture receives only about 5 percent” (Chief Executive Officer, Firm B). Therefore, despite leading to a higher availability of investor capital (see Section 5.1), strong policy-induced market growth may make investments in exploitation for companies pursuing less mature technologies prohibitively difficult, resulting in a “third valley of death” which “can be extremely difficult to overcome” (Scientist C).
Table 7: Mechanisms through which the technological maturity of a company’s products moderates the effect of policy-induced market growth on the balance between exploration and exploitation

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Exemplary Quote</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lack of physically mature product or manufacturing equipment</td>
<td>“The Renewable Sources Act puts the best available technology on the roof.”</td>
<td>Firm A, Chief Operating Officer</td>
</tr>
<tr>
<td></td>
<td>&quot;In those earlier days you are all about R&amp;D because you are a new company.”</td>
<td>Firm B, Chief Executive Officer</td>
</tr>
<tr>
<td></td>
<td>“We are still a pre-commercial company, so every dollar we raise is all going into R&amp;D.”</td>
<td>Firm D, Member Board of Directors</td>
</tr>
<tr>
<td></td>
<td>“The total number of CPV deployed in 2010 [...] was about 8 to 10 megawatts. The year before, in 2009, it was about 2 megawatts. Because the technology is so new, whatever booms were happening in PV earlier, CPV was not commercially ready to capitalize on those booms.”</td>
<td>Firm H, Chief Strategy Officer</td>
</tr>
<tr>
<td></td>
<td>“Less mature technologies simply were not there when the market support was introduced. Now, the others have a lead which means that it becomes more difficult [for less mature technologies to catch up].”</td>
<td>Scientist B</td>
</tr>
<tr>
<td>Higher barrier to market entry due to lacking economies of scale</td>
<td>“A few years ago you could build a 20 MW pilot and sell at a reasonable price. Now, 100 MW sounds more reasonable.”</td>
<td>Firm C, Director Business Development</td>
</tr>
<tr>
<td></td>
<td>“Nowadays, it’s difficult to enter the market as a player with great R&amp;D since you have to reach 5 GW scale to be competitive.”</td>
<td>Firm E, President</td>
</tr>
<tr>
<td></td>
<td>“I think there is still a significant interest in truly innovative early-stage ideas and then there are people that are willing to invest when you are almost at guaranteed success. But the amount of investments where people want to take you from being a commercial company with significant deployments to being a major volume player, that is a tough place to get investments because you are really not investing in the next widget. You really need a lot of working capital to drive product opportunities and those kinds of things.”</td>
<td>Firm H, Chief Strategy Officer</td>
</tr>
<tr>
<td></td>
<td>“It is difficult for [firms pursuing new technologies]. What’s happening now is that there is a very big emphasis on cost reduction and cost reduction quickly. Cost reduction quickly comes from economies of scale, so I think it is more difficult for start-up companies to come in because they have to compete and they don’t have the capability to compete on economies of scale. They could try to compete with technology but technology is slow to develop.”</td>
<td>Firm I, Director Research and Development</td>
</tr>
</tbody>
</table>

To conclude, our study suggests that deployment policies will not prompt exploitation among firms pursuing less mature technologies to the same extent as among firms pursuing more mature technologies. Hence, we phrase the following proposition:

**P III:** The less mature a firm’s technology, the less policy-induced market growth will induce a firm to invest in exploitation relative to exploration.
5.3 Additional Factors Affecting a Firm’s Balance between Exploration and Exploitation

In the following, we describe three factors which, in addition to the causal mechanisms described in Sections 5.1 and 5.2, we suspected of influencing a firm’s balance between exploration and exploitation. While these factors are linked to deployment policies, either their impact on the exploration/exploitation balance or their relationship with deployment policies remains ambiguous. Therefore, rather than phrasing separate propositions, we describe their general impact on firm-level investments in technological learning and briefly discuss why their presence does not undermine the general validity of propositions P I to P III.

Market Expectations & Uncertainty: A possible rival explanation to the propositions I and II is that uncertainty about the future development of markets rather than market growth itself triggered the changes in the balance between exploration and exploitation we observe. Indeed, particularly due to the fact that demand is strongly policy-driven and market growth rates have been very high, firms in the PV industry have faced “considerable uncertainty” (Business Development, Firm A) regarding the development of markets. Yet, contrary to a proposition put forward by Nemet (2009), during our study we did not find clear evidence that this market uncertainty induces a shift of firm investments towards exploitation. Rather, the firm representatives we interviewed concordantly reported that “in an uncertain environment you are generally reluctant to make long-term commitments” (Chief Operating Officer, Firm C) which will “reduce R&D expenses” (Chief Executive Officer, Firm B) but will simultaneously lead to “less appetite […] for investments in production capacity” (Chief Operating Officer, Firm C). Generally, uncertainty therefore reduces corporate investments in both exploration and exploitation. Furthermore, the extent to which market uncertainty affects firm investments strongly depends on the amount of slack resources the companies possess, making investment strategies of larger firms with strong backup financing less susceptible to uncertain market development than those of smaller players that “have to calculate with every penny – particularly when they are cut off from policy support” (Director R&D, Firm I).

Factor Prices: In the literature factor prices have been found to play an important role for ‘inducing innovation’ (e.g., Popp, 2002, Newell et al., 1999). We found that in the case of the PV industry, the price for silicon had a strong impact on a firm’s decisions to explore or exploit as it changes the cost competitiveness of the different PV technologies relative to each other. In the period until 2009 the “potential of c-Si was distorted due to high silicon prices” (Director Business Development, Firm C), triggering a search for alternatives, particularly in thin-film technologies. In this sense, high factor prices in the case of PV have generally been connected with a rise in exploration activities. The factor price effect exists in parallel to the effects described in
propositions P I to P III and may in fact be linked to policy-induced market growth. Policy-induced market growth raises the demand for production factors which, in the case of insufficient supply, raises factor prices in the short-term. In the long-term, however, augmented demand for factors is likely to stimulate the building of new capacities for supply. If the bottleneck does not lie in the natural availability of the factor itself, the newly built capacities will not only resolve temporary shortages in factor supply but, due to economics of scale, may lead to a situation where the price of production factors falls below the one before the bottleneck occurred. Therefore, in the longer run, the effects we would expect due to changes in factor prices are in line with proposition II, which suggests that firms will focus on exploitation in times of strong market growth.

**Competitive Intensity:** Like factor prices, competitive intensity shows strong links to the construct of policy-induced market growth. Given a certain supply of technology, a growth in policy-induced demand should lower the competitive intensity within an industry. Interestingly, while we found market growth to induce firms to focus on exploitation in times of low competitive intensity, we did not find uniform evidence that stronger competition leads to a focus on either exploration or exploitation. Some companies reported that, as a result of increased competition they had raised funding for R&D, while others were reducing costs by exploiting the potential of learning-by-doing and economies of scale within their existing product portfolio: “There could be things other than R&D that you do when you face competitive intensity. Sourcing, choice of location and operational excellence are moving higher on the agenda. [...] It is important to consider what the competitive dimension is” (Chief Operating Officer, Firm C). These findings concur with the ambiguous picture in the existing literature. In fact, the way in which firms react to intensifying competition may depend on the firm’s specific core competencies that determine its propensity to pursue a differentiation or a cost-leadership strategy (Porter, 1980).

6 Discussion

In the following paragraphs we first discuss the implications of our findings for the existing literature. Subsequently, we present recommendations for the design of future deployment policies.

6.1 Implications for the Existing Literature

By investigating the detailed mechanisms through which deployment policies affect exploration and exploitation in the solar PV industry, our study contributes to the current literature in three ways. First, while the literature assumes that deployment policies induce innovation, it is a widely held
view that demand-side instruments are not well suited to foster radical or breakthrough innovations within the supported industry (see Section 2.2). Our empirical findings show that, in fact, deployment policies serve as an important catalyst for innovation beyond existing technological trajectories as they raise investor interest in an industry and thereby generate funding opportunities for young ventures pursuing innovative technologies. Furthermore, the majority of companies pursuing more mature technologies in our sample used parts of the income generated through policy-induced markets to explore alternative technologies. Although the investor effect and the positive income effect have been described in the more general literature on ‘demand as a driver of technical change’, particularly the first one has not received much attention in the discussion of deployment policies.

Second, whereas in general therefore deployment policies are appropriate means to foster both exploration and exploitation, we find that the degree to which they trigger these two modes of learning relative to each other depends on the rate of market growth. In times of high market growth, firms face a strong incentive to raise their investments in exploitation which is facilitated by an increased availability of off-the-shelf equipment. Since firms possess limited organizational resources which they can invest in the two modes of learning at each point in time, exploration investments do not rise at the same rate as exploitation investments. Surprisingly and in contrast to existing theory, we find that in the PV industry it is human rather than financial resources that lead to a trade-off between exploration and exploitation. We attribute this finding to the fact that a firm’s capacity to grow in terms of personnel is rather limited in the short term and that the availability of qualified personnel may be limited during high-growth phases.

Finally, by shedding more light on how the technological maturity of a firm’s product moderates the effect of deployment policies, our study provides more detailed insights into how deployment policies affect technological diversity within an industry. We find that, although deployment policies attract investors to the industry, they may raise the barriers to market entry for less mature technologies (see Section 5.2). Hence, with our study we offer more systematic support for anecdotal evidence presented by Menanteau (2000), Sandén (2005) and Sartorius (2005) that deployment policies may increase the risk of a technological lock-in into potentially inferior technologies (see Table A.5 in appendix). In fact, several of the company representatives and experts we interviewed stressed that the emerging PV technologies might be intrinsically superior to wafer-based crystalline PV. However, the firms pursuing the latter technologies reported that under existing conditions they could not compete with wafer-based PV and deliberately targeted niche markets such as building integrated PV. Three representatives from firms producing wafer-based PV independently pointed to similarities between the development of the PV industry and the history of video cassettes, the combustion engine and the semiconductor industry, alluding to the
fact that it is not always the best technology that wins. While deployment policies can therefore be used to create niche markets for environmental technologies, our results suggest that they need to be carefully designed to avoid favoring more advanced technological designs within these niches. In this sense, as proposed by Azar and Sandén (2011), deployment policies are not technology neutral and bear the risk of picking the wrong winner.

6.2 Implications for Policy Makers

Our study has important implications for the design of future deployment policies. Generally, our findings suggest that deployment policies are effective instruments for inducing innovation as they trigger investments in exploration and provide firms pursuing more mature technologies with the possibility to benefit from exploitation. Particularly the latter effect constitutes a distinct advantage of deployment policies since many effects such as economies of scale, learning-by-doing and the build-up of an equipment industry would be much harder – or even impossible – to achieve when using conventional R&D support and fostering sustained exploration.

However, as the discussion in the previous section shows, the benefits of deployment policies come at a cost. By fostering exploitation among more established technologies, deployment policies enhance the risk of a technological lock-in. Such a lock-in may be uncritical in the case that it is certain that these technologies meet present and future needs in terms of economic, ecological and societal dimensions. Given that technological and societal changes are inherently unpredictable, however, it seems advisable that policy makers maintain a certain technological diversity (Stirling, 2010). At present, for example, it still remains unclear whether wafer-based PV technology will be able to reach a cost level at which it can compete with conventional power sources such as coal, which justifies pursuing different technological options within PV (van den Heuvel and van den Bergh, 2009).

To reduce a potential adverse effect of deployment policies on technological diversity, we suggest three potential solutions. First, our findings imply that the risk of technological lock-ins can, at least to some extent, be reduced when avoiding extreme market growth rates, e.g., “beyond 40%” (Chief Technology Officer, Firm C). Slower market growth can be expected to lead to a slower widening of the cost gap between more and less mature technologies, giving the firms pursuing the latter more time to engage in capital- and time-consuming technology development. Lower growth rates may also help to reduce problems with public acceptance that result from high annual costs for technology support and in the past have led to sudden collapses of national PV markets, e.g., in Spain or Czech Republic. At the same time, however, slowing market growth in clean energy
technologies reduces the possibility to leverage the above-mentioned advantages of exploitation and has a detrimental effect on their diffusion which might be considered undesirable from an ecological point of view.

Besides keeping policy-induced market growth at appropriate levels, policy makers can design deployment policies in a way that staggering incentives according to different technologies. Clearly, there is a limit to how technology-specific such policies can be without causing excessive administrative costs. However, granting higher incentives for promising but less mature technologies – e.g., through higher feed-in tariffs for emerging PV technologies or even a special remuneration for particular designs such as organic PV – can help to build a portfolio of alternative technological options of which some may outperform current technologies in the future.

Finally, policy makers should complement deployment policies with R&D and venture support. Using policy instruments such as R&D subsidies or R&D tax credits in parallel to deployment policies can set incentives for firms to raise their level of exploration. Furthermore, by providing favorable conditions for start-ups, policy makers may help lowering the barriers to market entry and reduce the likelihood of a premature technological lock-in. In this sense, deployment policies should not be regarded as a substitute for supply-side innovation policies, but, on the contrary, require their increased use.

7 Limitations and Future Research

This study has some limitations which represent potentially fruitful avenues for future research. First, an important question to ask is whether the findings presented in proposition I to III are generalizable to sectors other than the PV industry. Anecdotal evidence from the wind industry seems to suggest that the propositions may be well applicable to other sectors. For example, Karnøe (1990), Garud and Karnøe (2003) and Nemet (2009) report that strong growth in the case of the Californian wind industry might have induced firms to shift their resources from technology development to production. However, strong shifts between exploration and exploitation might not be as pronounced in industries with bigger firms that possess a higher endowment with human resources and more stable organizational structures. Furthermore, PV seems to be special in that products in this industry are rather commoditized, making economies of scale and learning-by-doing important levers for cost reduction. Therefore, even if the propositions are valid on a cross-sector basis, they might not automatically imply an increased risk of technological lock-in in other sectors to the same extent as in the PV industry.

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Second, our research provides initial insights into how deployment policies affect the balance between explorative and exploitative learning. Nevertheless, it remains unclear to which extent policymakers should foster technological diversity rather than advancing a small number of technologies on an existing trajectory. Given that maintaining a large portfolio of technologies is a costly endeavor and may prevent every single one from fully reaping the benefits of exploitation, what are the relevant criteria that determine ‘optimal’ diversity of a technology portfolio? While some first promising steps have been made in measuring and valuing diversity (see e.g., Stirling, 2010, van den Bergh, 2008), further research seems necessary to provide more empirically grounded recommendations for when and how policymakers should foster technological diversity. In this regard, it seems important to take a closer look at the individual instruments fostering deployment, such as feed-in tariffs or technology standards, and scrutinize to which extent they may differently affect exploration and exploitation.

8 Conclusion

Our study contributes to a better understanding of how deployment policies induce technological innovation. Since previous work suggested that strong policy-induced market growth may create an incentive for firms to focus on exploitation to the detriment of exploration, we investigated the question of how deployment policies affect corporate investments in these two modes of learning. We suggest that policy-induced market growth leads to an absolute increase in the level of firm investments in exploration as it raises firms’ income and attracts venture capital investors to the industry. The degree to which deployment policies induce firms to invest in exploitative learning, however, is highly dependent on the maturity of the firm’s product technology. For firms pursuing more mature PV technologies, an increase in policy-induced market growth reduces the immediate need to invest in longer-term explorative activities, sets strong incentives to use scarce human resources for exploitation and facilitates exploitation through the emergence of specialized manufacturing equipment. Firms pursuing less mature PV technologies are often not in a position to make use of exploitation to the same extent as they may lack a functioning product or the necessary production equipment. Since exploitation is accompanied by benefits from learning-by-doing and economies of scale, strong policy-induced market growth raises the barriers to market entry for emerging technologies. Our findings have important implications for the design of deployment policies. We find deployment policies to be generally effective in fostering technological innovation. However, deployment policies need to be designed with care and should be complemented by supply-side measures to alleviate the risk of a technological lock-in.
References


Malerba, F. (2009). Increase Learning, Break Knowledge Lock-ins and Foster Dynamic Complementarities: Evolutionary and System Perspectives on Technology Policy in Industrial


## Table A.1: Company reports covered in key word search

<table>
<thead>
<tr>
<th>Company name</th>
<th>Country of Origin</th>
<th>Years covered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arise Technologies Corp.</td>
<td>Canada</td>
<td>2003-2010</td>
</tr>
<tr>
<td>Canadian Solar, Inc.</td>
<td>China</td>
<td>2006-2010</td>
</tr>
<tr>
<td>China Sunergy</td>
<td>China</td>
<td>2006-2010</td>
</tr>
<tr>
<td>Conergy AG</td>
<td>Germany</td>
<td>2006-2010</td>
</tr>
<tr>
<td>Day4 Energy, Inc.</td>
<td>Canada</td>
<td>2008-2010</td>
</tr>
<tr>
<td>Ersol Solar AG</td>
<td>Germany</td>
<td>2005-2009</td>
</tr>
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<td>Evergreen Solar, Inc.</td>
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<td>USA</td>
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</tr>
<tr>
<td>Trina Solar Ltd.</td>
<td>China</td>
<td>2006-2010</td>
</tr>
<tr>
<td>Yingli Green Energy Holding Co. Ltd.</td>
<td>China</td>
<td>2007-2010</td>
</tr>
</tbody>
</table>
Table A.2: Typical interview guide as used in the case study

<table>
<thead>
<tr>
<th>Category</th>
<th>Exemplary Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investments in exploration</td>
<td>How has your R&amp;D intensity developed in the past years? Why?</td>
</tr>
<tr>
<td></td>
<td>Are you planning to increase or decrease your R&amp;D investments in the future? Why?</td>
</tr>
<tr>
<td></td>
<td>What determines how much your company invests in R&amp;D relative to other expenses?</td>
</tr>
<tr>
<td>Investments in exploitation</td>
<td>What determines how much you invest in production capacity?</td>
</tr>
<tr>
<td></td>
<td>Are you planning to increase or decrease your investments in production capacity the future? Why?</td>
</tr>
<tr>
<td>Trade-off between investments in exploration and</td>
<td>Is there a trade-off between investments in R&amp;D and production capacity? Why (not)?</td>
</tr>
<tr>
<td>exploitation</td>
<td></td>
</tr>
<tr>
<td>Role of deployment policies in the PV sector</td>
<td>What is currently the main driver of PV markets?</td>
</tr>
<tr>
<td></td>
<td>Which role does public policy play for the photovoltaic market?</td>
</tr>
<tr>
<td>Link between deployment policies and investments in</td>
<td>How does policy-induced market growth affect investments in production capacity?</td>
</tr>
<tr>
<td>exploration and exploitation</td>
<td>How does policy-induced market growth affect investments in R&amp;D?</td>
</tr>
<tr>
<td></td>
<td>In times of strong market growth, would you invest in R&amp;D or production capacity?</td>
</tr>
<tr>
<td></td>
<td>In times of strong growth have you observed bottlenecks in terms of organizational resources? In which areas?</td>
</tr>
<tr>
<td>Potential additional factors affecting a firm’s</td>
<td>Which role do market expectations or market uncertainty play for your investments in R&amp;D or production capacity?</td>
</tr>
<tr>
<td>balance between exploration and exploitation</td>
<td>Which role do factor prices, such as polysilicon prices, play for your investments in R&amp;D?</td>
</tr>
<tr>
<td></td>
<td>Which role does the competitive intensity in the market play for your R&amp;D investments?</td>
</tr>
<tr>
<td></td>
<td>In the past, have you collaborated with equipment manufacturers? Are you planning to outsource part of your R&amp;D to equipment manufacturers?</td>
</tr>
<tr>
<td></td>
<td>In the past, have you collaborated with public research institutes? Are you planning to outsource part of your R&amp;D to public research institutes?</td>
</tr>
</tbody>
</table>
Table A.3: Evidence for the importance of deployment policies in the PV sector

<table>
<thead>
<tr>
<th>Exemplary Quote</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>„It is the policy-induced markets that allow us to sell our PV products and fuel our research. Especially at the beginning, the renewable energy law played an important role as it created the market. “</td>
<td>Firm A, Policy Department</td>
</tr>
<tr>
<td>„Currently, you can substitute the word ‘market’ with ‘policy’. But we want to move beyond this. “</td>
<td>Firm A, Chief Operating Officer</td>
</tr>
<tr>
<td>“Without policy support, there would be no market [...] “</td>
<td>Firm A, Business Development</td>
</tr>
<tr>
<td>“I think the whole industry is based on the notion that governments give PV a grace period until we can be competitive. [..] The next couple of years, markets will be driven by policies. “</td>
<td>Firm C, Director Business Development</td>
</tr>
<tr>
<td>“We believe that PV has a position in the future. We think that also governments believe that and help us move forward until we are competitive. “</td>
<td>Firm C, Director Business Development</td>
</tr>
<tr>
<td>“The feed-in tariffs obviously have created tremendous market demand drivers in Germany and throughout Europe, whereas we have tax credits mostly and subsidies as opposed to feed-in tariffs here in the US. “</td>
<td>Firm G, Chief Executive Officer</td>
</tr>
<tr>
<td>“The market development is driven by policy support. “</td>
<td>Firm I, President</td>
</tr>
<tr>
<td>Policy support is critical. [..] The policy support and feed-in tariffs had a fantastic effect on the market and we are now actually starting to see much more the effect of that not just in terms of how many modules are sold and how many companies there are but also in terms of cost. [..] Policy support is vital for companies like us to be able to continue to play our role. “</td>
<td>Firm I, Director Research and Development</td>
</tr>
<tr>
<td>“The feed-in tariffs, especially in Germany, have led to strong growth. “</td>
<td>Scientist B</td>
</tr>
<tr>
<td>“A market is a necessary condition. For this, we need policy support. “</td>
<td>Investor A</td>
</tr>
<tr>
<td>“Policy support is very important for the PV industry. “</td>
<td>Equipment Manufacturer B</td>
</tr>
<tr>
<td>&quot;Market support is necessary to solve the hen-egg problem. A couple of years ago, photovoltaic technology was extremely expensive and nobody used it for normal, terrestrial generation of electricity. Because it was expensive and nobody used it, nobody built new plants. Because nobody built new plants, the prices didn’t come down. Today, with the help of policy, this vicious circle has been broken. “</td>
<td>Market Analyst/Consultant C</td>
</tr>
</tbody>
</table>
Table A.4: Pearson correlations between market growth and firm-level indicators for firms pursuing wafer-based crystalline PV (N=164, t=7)

<table>
<thead>
<tr>
<th></th>
<th>Market growth in GW</th>
<th>Market growth in %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No lag</td>
<td>Lag = 1</td>
</tr>
<tr>
<td>R&amp;D investments (USD)</td>
<td>0.80*</td>
<td>0.58</td>
</tr>
<tr>
<td>Increase in production capacity (GW)</td>
<td>0.98**</td>
<td>0.23</td>
</tr>
<tr>
<td>R&amp;D intensity (%)</td>
<td>-0.48</td>
<td>-0.55</td>
</tr>
</tbody>
</table>

* p < 0.05, ** p < 0.01
Table A.5: Statements indicating an increasing risk of a technological lock-in in the PV industry

<table>
<thead>
<tr>
<th>Exemplary Quote</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>“With really innovative, novel technologies you don’t have a chance to enter the market any longer. I don’t think that, in the sense of Green, there will be a billion-dollar market for third generation PV technologies.”</td>
<td>Firm B, Chief Executive Officer</td>
</tr>
<tr>
<td>“We studied a stream of technology start-ups. Only very few get funding. It is very difficult to enter the market with a new start-up.”</td>
<td>Firm C, Director Business Development</td>
</tr>
<tr>
<td>“Coming from the semiconductor industry, this sounds very familiar. There were alternatives to RAM, too. They had to reduce costs significantly but many weren’t able to do this.”</td>
<td>Firm C, Director Business Development</td>
</tr>
<tr>
<td>“The development in PV is similar to the one of the internal combustion engine. The Otto Motor was not necessarily better than alternatives, but many incremental improvements ultimately led the concept to success.”</td>
<td>Firm E, President</td>
</tr>
<tr>
<td>“[T]he dramatic growth in the crystalline PV industry, as accelerated by feed-in tariffs and alike, has caused a scaling and a cost-reduction […] that has made it very difficult for CIGS to enter the market. In fact, the start-up innovative CIGS companies either have run out of capital or are getting acquired by Asian companies because they were not able to get through their commercial window of opportunity.”</td>
<td>Firm G, Chief Executive Officer</td>
</tr>
<tr>
<td>“One thing which might make crystalline PV the winner is that PV technology is very slow to develop as you can see with the increase of the efficiency over time. It is one or two percent over a ten year period and the costs have gone down very rapidly thanks to economies of scale. So, it is obvious that there are technologies out there that can displace c-Si in terms of cost and performance but whether they can do that in time is very questionable.”</td>
<td>Firm I, Director Research and Development</td>
</tr>
<tr>
<td>“It is not always the best technology that wins, that is probably true.”</td>
<td>Scientist B</td>
</tr>
<tr>
<td>“Scientists have continuously told us that optical storage mediums are better. Nevertheless, hard drives are still dominating the market. Why? Because for an industry which has reached a certain level of maturity and a certain volume it is much easier to use some percentage of research. And in the case of crystalline silicon – be it mono or poly – these are amounts of billion euros, whereas thin-film technologies are basically still supported through tax money, public research funding. [...] And, as a consequence, these technologies struggle against an established technology that advances with great strides.”</td>
<td>Market Analyst/Consultant C</td>
</tr>
<tr>
<td>“The crystalline technology is definitely the worst technology we have. But it is one that is sufficient to produce electricity cheaper than coal. If we looked at what intrinsically is the best technology, this would be the so-called third-generation PV.”</td>
<td>Market Analyst/Consultant C</td>
</tr>
<tr>
<td>“There probably is something like a time window. There was a time window during which you could develop technologies and at some point in time the window will close again. And you won’t be able to compensate for this with public research because, in my opinion, it doesn’t generate the same dynamics as a fast growing market.”</td>
<td>Policy Maker B</td>
</tr>
</tbody>
</table>
Paper II
The Role of Inter-Firm Knowledge Spillovers for Innovation in Environmental Technologies – Evidence from the Solar Photovoltaic Industry

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Abstract

Innovation in environmental technologies is often described as an important source of competitive advantage for both firms and countries. However, at the same time the literature is full of examples that show how knowledge generated through innovation can quickly spill over to other firms, thereby undermining the competitive edge a company might have. Responding to a lack of research that studies knowledge spillovers for environmental technologies on the firm level, in this paper we use panel data regression analysis to investigate the drivers of firm-level technological innovation in the solar photovoltaic (PV) industry. We find clear evidence for the existence of inter-firm knowledge spillovers. In accordance with the literature on absorptive capacity, absorption of external knowledge is positively associated with firms’ prior knowledge generated through R&D. However, at the same time, we provide evidence that besides investments in R&D, investments in production equipment have driven inter-firm knowledge spillovers in the PV industry. Our findings have major implications for the literature linking environmental innovation and competitive advantage. Moreover, by pointing to the role of process technology as a means of assimilating and exploiting external knowledge, we highlight an important but strongly neglected channel of absorptive capacity.

Keywords: Environmental Innovation, Competitive Advantage, Knowledge Spillovers, Technological Innovation, Absorptive Capacity, Solar Photovoltaic Power
1 Introduction

Pressing societal issues such as climate change and resource depletion have given rise to a dynamically growing stream of literature that deals with innovation in environmental technologies. Spurred by aspirations in society and public policy to develop and deploy technologies that reduce the adverse effects of economic activity on natural ecosystems, authors have studied antecedents and outcomes of environmental innovation (e.g., Horbach, 2008). As a particularly appealing proposition, it has been suggested that innovation in environmental technologies not only benefits the natural environment but may also increase the economic competitiveness of the innovating firms. Given the multi-trillion dollar market for environmental technologies that is expected to emerge (BMU, 2012), a number of scholars have put forward that firms which take a proactive role will be able to reap considerable benefits in the future. (Buysse and Verbeke, 2003, Shrivastava, 1995). Beyond this, in what has become known as the ‘Porter Hypothesis’, Porter and van der Linde (1995) argued that governments should put in place strict environmental regulations to spur innovation which they believed to enhance the competitiveness of firms and of the country where these are located.

While the idea that environmental policies can induce firms to invest in technological innovation has been supported by a wide range of empirical studies, the question whether environmental innovation in turn leads to a competitive advantage of firms remains much more controversial (Ambec et al., 2011). On the one hand, starting with the work of Schumpeter (1912), the literature has continuously stressed technological innovation as an important contributor to the competitiveness of firms and economic growth (Henderson and Clark, 1990, Christensen and Bower, 1996, Tushman and Anderson, 1986). On the other hand, there is a long line of literature that shows how knowledge generated through innovation can spill over to other firms through a variety of channels which reduces the ability of firms to appropriate the returns from their investment in innovation (Griliches, 1992, Mansfield, 1985). Strong knowledge spillovers can undermine any short-term competitive advantage a firm is able to generate through innovation (McEvily and Chakravarthy, 2002). This notion is backed by the resource-based view which posits that to support a longer-term competitive advantage, the resources underlying firm strategies need to be, amongst other attributes, rare and inimitable (Barney, 2001, Barney, 1991, Wernerfelt, 1984).

The question whether innovation can lead to competitive advantages is of importance for all industries. Yet, it is particularly relevant for environmental technologies since a) much more so than other technologies they have been the subject of political support in recent years and b) almost always have policies been implemented to increase the competitiveness of domestic industries. Despite their potentially important role, up to this point the notion of inter-firm
knowledge spillovers has received relatively little attention in the debate on environmental innovation and firm competitive advantage. Existing studies predominantly examine spillovers between countries or industries (e.g., Bosetti et al., 2008, Nemet, 2012), not allowing to derive implications for the competitiveness of firms. Moreover, it currently remains unclear what drives knowledge spillovers between firms pursuing environmental innovation. While the literature on absorptive capacity has stressed the firm’s own prior knowledge as an important facilitator of knowledge absorption (Cohen and Levinthal, 1990), knowledge may also be transferred through the exchange of people or technological artefacts, such as machinery (Teece, 1998). Despite anecdotal evidence of their existence, we lack systematic evidence of the role that these channels of knowledge absorption play in the case of environmental innovation.

Responding to the lack of research, in this paper we address the question which role inter-firm knowledge spillovers play for innovation in environmental technologies. Towards this end, we draw on the case of solar photovoltaic (PV) technology as an important environmental technology and use panel data regression to investigate the drivers of technological innovation for 23 publicly listed firms producing wafer-based crystalline silicon PV cells from 2000 to 2011. We find strong evidence that improvements in the cost-to-performance ratio of PV technologies are driven by inter-firm knowledge spillovers. According to our results, these spillovers are facilitated not only by the firm’s investments in their own knowledge but also investments in standardized manufacturing equipment. Our findings have major implications for the literature on environmental innovation which needs to refine its propositions and investigate the prevalence, origins and effects of knowledge spillovers. In addition, our work contributes to a better understanding of the mechanisms that enable firms to capture and exploit external knowledge. We highlight standardized manufacturing equipment as a potentially important channel of knowledge absorption which so far has received limited attention in the literature on absorptive capacity. Considering that standardized manufacturing equipment is used in a steadily rising number of industries, we call for a closer investigation of this channel of absorptive capacity in future research.

The remainder of the paper is organized as follows: In Section 2 we derive six hypotheses on the role of knowledge spillovers and absorptive capacity for innovation in environmental technologies. After introducing the research case in Section 3, we then discuss our research method in Section 4. The results of our study are presented in Section 5, followed by a discussion of their implications for the literature, corporate managers and policy makers (Section 6). The paper concludes with a description of limitations, suggestions for future research and a brief summary of the main results.
2 Literature Review and Hypotheses

2.1 Knowledge Spillovers as a Driver of Technological Innovation

Knowledge constitutes an important economic resource that is at the heart of firms and their ability to excel in competitive markets (Grant, 1996). To generate new knowledge, firms engage in innovation which has been defined as an effort of combining existing knowledge in a way that increases its utility for the innovator (Schumpeter, 1942, Kogut and Zander, 1992). While internally held knowledge of the firm is an important source when developing new products (Smith et al., 2005), it has been pointed out that firms increasingly draw on knowledge from external sources, such as competitors, suppliers, universities or public research institutes (Powell et al., 1996).

To tap external knowledge sources, firms form alliances (Mowery et al., 1996, Harrison et al., 2001, Rothaermel and Deeds, 2004), draw on acquisitions (Ranft and Lord, 2002, Cassiman et al., 2005) and engage in patent licensing (Pitkethly, 2001). However, besides making use of these deliberate means of knowledge sharing, firms also incur involuntary leakages of knowledge, so-called knowledge spillovers (Arrow, 1962a, Griliches, 1992, Mansfield, 1985). Knowledge spillovers operate through a variety of channels. First, it has been shown that knowledge which is codified in the form of documents, such as patents, manuals or scientific publications, can be easily accessed and exploited by others (Appleyard, 1996). Although patenting aims at preventing the direct imitation of innovations, the publication of patents also enhances knowledge transfer as it requires firms to codify and publish the knowledge related to their innovation. Moreover, the time for which patents confer the appropriability of a firm’s innovation is generally limited (Kaiser, 2002). Second, knowledge can be transferred through people as an important knowledge carrier. Employees of firms can share knowledge through personal interaction or, if knowledge cannot be articulated, by simply observing others’ behavior (Polanyi, 1962). Hiring, relocating or dismissing personnel simultaneously transfers the knowledge an employee has gathered over time, enabling firms to benefit from knowledge of other firms (March, 1991, Agarwal et al., 2004). Third, knowledge is embodied in technical artefacts which frequently serve as a source of knowledge. By developing a technology, the relevant knowledge of a firm gets embedded in the product and can be accessed by outsiders (e.g., through reverse engineering) as soon as the product enters the public sphere (Teece, 1998).

In reality, the prevalence of each of the different channels described above is likely to determine the extent to and geographic scope at which knowledge spillovers take place. While a high tacitness of knowledge has been connected with more geographically bounded spillovers (Audretsch and Feldman, 1996), there is a trend that with the globalization of flows in goods, people and information all previously-mentioned mechanisms increasingly operate at an international level.
(Watanabe et al., 2001). Still, the existence of strong knowledge spillovers does not automatically imply an important role for firm-level innovation. Legal conditions in countries and firms, such as patent regimes or the design of work contracts, can significantly limit the degree to which knowledge that has spilled over to a firm can be utilized in its products (Cohen et al., 2002). In the following we therefore discuss empirical findings related to the role of knowledge spillovers for innovation to derive hypotheses pertaining to the role of interfirm knowledge spillovers and factors driving them.

### 2.2 Inter-firm Knowledge Spillovers as a Driver of Technological Innovation

In line with the large number of different channels through which knowledge can flow, the literature has found strong evidence for an effect of inter-firm knowledge spillovers on firm-level technological innovation. For example, Henderson and Cockburn (1996) find knowledge spillovers from other firms to significantly affect the research outcome of firms in the pharmaceutical industry. Knowledge spillovers between firms are often cited as the main reason for the occurrence of innovation clusters (Agarwal et al., 2008), such as the Silicon Valley, or localized innovation systems (Breschi and Lissoni, 2001) and have also been referred to when trying to explain the catching up of countries in particular industries (Bernstein and Mohnen, 1998).

Surprisingly, despite their particular relevance for environmental technologies and the strong evidence for their existence in other sectors, to our knowledge there are almost no empirical studies available that investigate inter-firm knowledge-spillovers for environmental products. A notable exception is Watanabe et al. (2002) who provide evidence for the existence of knowledge spillovers in the photovoltaic industry. Drawing on data from 8 Japanese firms, they find that firm-external knowledge stocks significantly affected firm-level patent applications, production volume, prices of solar cells and learning. However, Watanabe et al.’s (2002) analysis is limited to Japan, not accounting for the possibility that innovation in the Japanese PV industry may be driven by knowledge originating in other countries. In this paper, we build upon and extend the analysis of Watanabe and colleagues. In line with the abounding evidence in the literature, we expect knowledge originating in other firms to have a significant effect on innovation in a firm’s environmental technologies. However, given the strongly evolutionary, cumulative nature of the research process (Malerba and Orsenigo, 2000), we would expect knowledge developed by the firm itself to play a more important role in advancing a firm’s technology than knowledge developed outside the firm. Moreover, for the knowledge to be of use for a firm, we would presume that a minimum technological proximity between firms’ technologies needs to be given for knowledge spillovers to occur (Lane and Lubatkin, 1998). For this reason and since we are ultimately
interested in using the results to derive implications for competitive dynamics, we focus on inter-
firm knowledge spillovers within one industry. We hence, phrase the following two hypotheses:

H1 a) Knowledge developed by other firms in an industry has a positive effect on innovation in a
firm’s environmental technology.

H1 b) Knowledge developed by other firms in an industry has a smaller marginal effect on
innovation in a firm’s environmental technology than the knowledge developed by the firm
itself.

2.3 Absorptive Capacity as a Moderator for the Effect of Knowledge Spillovers

The hypotheses derived in the previous section suggest that firms may benefit from knowledge
spillovers from external private and public research. However, as previous research has pointed out,
benefits from spillovers do not come to firms as a ‘manna from heaven’ but require distinct efforts
of identifying, integrating and using the external knowledge (Cohen and Levinthal, 1990). The “set
of organizational routines and processes by which firms acquire, assimilate, transform and exploit
knowledge” (Zahra and George, 2002, p.186) has been summarized under the term “absorptive
capacity”. The exact effect of a firm’s absorptive capacity has been found to depend on its
organizational structure (van den Bosch et al., 1999, Lenox and King, 2004, Jansen et al., 2005),
the source of knowledge (Schmidt, 2010) and the proximity between firm-internal and firm-external
knowledge (Nooteboom et al., 2007, Mowery et al., 1998, Lane and Lubatkin, 1998). As a consistent
result, however, empirical studies have shown that the level of absorptive capacity a firm possesses
is strongly related to its prior investments in knowledge (Cohen and Levinthal, 1990). A larger
amount of firm-internal knowledge that is complementary to external knowledge improves a firm’s
capacity to appropriate outside knowledge from other firms (Lane et al., 2006, Tsai, 2001).

More recently, it has been suggested that the nature of absorptive capacity may look different
depending on the firm’s industry (Arbussa and Coenders, 2007) and the level of maturity of the
technology in question (Lim, 2009). Lim (2009) proposes that over the course of the technology life-
cycle the type of knowledge firms acquire changes from general scientific knowledge to knowledge
embedded in tools and processes. He concludes that in later stages of the technology life-cycle the
main task of R&D therefore lies in integrating knowledge from suppliers that possess the relevant
knowledge embedded in machinery, e.g., through research collaborations or licensing. We go beyond
his proposition by arguing that if indeed industry knowledge becomes embedded in machinery over
time, this might in fact open up investment in manufacturing equipment as a separate channel of
absorptive capacity that is relatively independent of investments in R&D. If manufacturing equipment is sufficiently standardized and easy to operate, it might enable firms without a large stock of prior knowledge to quickly enter the market and produce at low costs (Zander and Kogut, 1995).

In sum, we would expect a firm’s absorptive capacity to moderate the degree to which external knowledge affects a firm’s innovation in environmental technology. In the following, we therefore state two hypotheses which propose firm-internal prior knowledge and investments in manufacturing equipment as two factors moderating the effect of inter-firm knowledge spillovers. Concluding our literature review, Figure 1 summarizes the hypotheses underlying our analysis.

H2 a) The effect of knowledge developed by other firms in an industry on innovation in a firm’s environmental technology is positively moderated by the knowledge developed by the firm itself.

H2 b) The effect of knowledge developed by other firms in an industry on innovation in a firm’s environmental technology is positively moderated by the firm’s investment in manufacturing equipment.
3 Research Case

As the research case for our analysis we choose the solar photovoltaic industry. Solar photovoltaics (PV) is an important environmental technology which offers considerable potential for reducing local air pollution and mitigating the adverse impacts of the energy sector on the global climate system. Based on semiconductor technology, PV converts sunlight into electric power, thereby causing fewer emissions over the life cycle than means of electricity production based on the combustion of fossil fuels like coal or gas. In recent years, an industry has emerged which in 2011 already generated global revenues of more than $90 bn (Solarbuzz, 2012) and has grown at an astonishing average rate of more than 40% percent per year since 2000 (EPIA, 2012). Within this market, several PV technologies compete for market share with the biggest proportion being assumed by wafer-based crystalline (c-Si) PV, followed by thin-film PV technologies made from materials such as Cadmium Telluride (CdTe) or Copper Indium Gallium Selenide (CIGS). As PV is not yet cost competitive with conventional means of electricity generation, most of this market growth has been triggered by policy support on both the supply and demand side. Besides environmental considerations, a key motivation for government interventions was the hope of increasing economic competitiveness and generating domestic jobs in a dynamic high-tech industry.

![Figure 2: Development of market shares of leading PV cell producers (data from Photon, 2012)](image-url)
Despite the great hopes that have been set on this technology, in the past companies have not been able to maintain their competitive advantage. Figure 2 shows the three companies producing solar crystalline PV cells – the main component of conventional PV modules – which since 2000 have assumed the position of the market leader. In addition, Figure 3 displays the distribution of market shares in the PV industry according to the origin of companies. Within a period of only eleven years two new entrants have been able to become market leaders for a relatively standardized product. At the same time, Chinese firms have been able to raise their share in production of PV cells from only 4% in 2004 to almost 70% in 2011 (Photon, 2012).

Together, these developments raise the question of which role knowledge spillovers might have played in driving changes in leadership positions in the solar PV industry. Recent anecdotal evidence suggests that Chinese manufacturers of PV cells may have significantly benefited from the emergence of an industry that develops and sells standardized PV manufacturing equipment (de la Tour et al., 2011). From 2004 to 2011 the global market for specialized PV equipment has grown from 400 M to 8,700 M USD with German and US companies assuming the largest share of the market (VSLI Research, 2011). To develop the equipment, equipment manufacturers closely collaborated with PV manufacturers in their home countries and embodied the resulting knowledge in their products. Later the production equipment was sold to companies not involved in its development, especially Asian producers of PV cells that were quickly ramping up their manufacturing capacity. According to de la Tour et al. (2011), usually the purchase of the equipment included training sessions for the employees in Chinese firms for how to operate it. As a result, the export of manufacturing equipment to China might have indirectly given Chinese manufacturers access to the knowledge of German and US manufacturers and could have enabled them to even produce at a lower cost than the incumbent firms. A report published by the German Expert Commission on Research and Innovation, for example, comes to the conclusion that “Germany benefited from the global growth of the photovoltaic industry in the area of production equipment. Substantial and technologically crucial parts of today’s production lines in China have been supplied by German equipment manufacturers. At the same time, the export of turn-key equipment was the decisive path of knowledge transfer to Chinese companies in the photovoltaic industry. [...] The revenue of the German producers of processing and manufacturing equipment in the area of photovoltaics amounted to 2.5 BN EUR in 2010. The export quota was 85 percent, 74 percent of sales went to Asia” (Backes-Gellner et al., 2012). In our analysis we test whether improvements in product cost and performance of PV cells have indeed been driven by inter-firm knowledge spillovers and whether, in line with hypotheses 2a and 2b, these spillovers were driven by firms’ investment in own knowledge and/or manufacturing equipment.
4 Data and Method

4.1 Sample

To test our hypotheses, we analyzed data for 23 publicly listed producers of wafer-based c-Si PV cells for the time from 2000 to 2011. Based on Breyer (2010) and Photon (2012), we first compiled a list of publicly listed companies active in different parts of the value chain in the solar photovoltaic industry. This list was narrowed down to firms pursuing wafer-based c-Si PV technology since our analysis of knowledge spillovers required a minimum technological proximity between firms. Among the different PV technologies available, we decided to focus on wafer-based c-Si PV since with a market share of more than 87% in 2011, it is the technology currently pursued by most firms in the industry (Photon, 2012). PV modules from crystalline PV are manufactured using a multi-stage process in which silicon is cast into ingots, cut into wafers, further processed to cells and finally assembled to modules. Of these steps, the transformation from wafers to cells is generally considered one of the most technologically challenging parts with large potential for innovation. Since we are interested in observing innovation of firms in the PV industry, we therefore further limited the scope of firms included in our analysis to those that covered at least the value chain step of cell
production. Among the firms that fulfill this criterion are both conglomerates and smaller pure-play companies. Since conglomerates generally do not report the data required for analysis on a sufficiently disaggregated level, companies in our sample are exclusively comprised of pure-play manufacturers of PV cells. A list of these companies with their country of origin, production and share in global production is provided in Table A.1 in the appendix. Overall, the companies contained in our sample produced 17.04 GW of PV cells in 2011, which corresponds to a share of 45.8% in the global PV market or 52.1% in the market for crystalline silicon PV cells.

4.2 Variables

Our hypotheses suggest linkages between four key variables: Innovation in a firm’s environmental technology as the dependent variable, the knowledge developed by other firms in the industry, the firm’s own knowledge and investments in manufacturing equipment as independent variables. In the following, we explain how we operationalized each of these variables and discuss the controls we included in our model.

Dependent variable

Innovation in a firm’s environmental technology was measured as a change in the ratio between the firm’s product costs and product performance. According to Utterback and Abernathy (1975), this indicator is well suited to describe advances of product technology within an established technological trajectory. In the PV industry, the most widely used measure to describe the cost-to-performance ratio of PV cells is by dividing the cells’ nominal power capacity in Watt peak (Wp) by its production cost, usually in USD (Suntech Power Holdings Co., 2012). Simply speaking, this measure expresses the costs associated with a product that, in a given location, allows a customer to generate a particular amount of electricity. Data on the customer price per Watt peak is often directly reported by companies in their annual reports and SEC filings or can be calculated by dividing a company’s sales in USD by its sales volume in Wp. While for companies producing only PV cells we extracted prices for cells, companies that further process these cells into modules often only report prices for modules, i.e., cells that are assembled in an aluminum frame. Therefore, for the latter companies, we employed module instead of cell prices. This was considered an appropriate approach since in our analysis we look at intra-firm changes over time, i.e., price differences between firms due to additional processing have no effect on our model outcome. To translate prices into costs, we multiplied the customer price per Watt peak by “1 – the firms’ gross profit margin, i.e., gross profit per sales”. According to firm representatives of PV cell manufacturers that we
consulted, this procedure yields a good approximation for the performance-to-cost ration in USD per Watt and is also commonly employed in the PV industry itself.

**Independent variables**

As is common in the literature, measures for firm knowledge stocks were constructed based on publicly available data on annual R&D investments (Kaiser, 2002). Differences in reporting standards across countries are not an issue as in our model we focus on changes in knowledge stocks over time within a particular firm. When constructing the ‘knowledge stock for other firms in the industry’, we could not rely on R&D expenditures from annual reports since the majority of firms in the PV industry are not publicly listed and knowledge may spill over from firms other than those producing PV cells. We therefore drew on data from Breyer et al. (2010) who provide a detailed estimate of annual private R&D expenditures in the PV industry over time based on patent data.

Two important factors to be taken into account when creating knowledge stocks from R&D data are the assumed knowledge depreciation rate and the time lag between R&D investments and the improvement of a firm’s technology (Esposti and Pierani, 2003). As the basis for our study, we relied on findings by Watanabe et al. (2002) who conducted a survey among 19 Japanese firms in the PV sector to identify the before-mentioned factors. Drawing on their results we set the knowledge depreciation rate to 20% and the time lag for firm-internal R&D to 3 years. The lags for firm-external R&D are chosen to be 5 years. To account for uncertainty and the possibility that factors might have changed since the study by Watanabe et al. (2002), for each of our three independent variables we also constructed and tested knowledge stocks with depreciation rates of 0%, 10%, 30% and 40% and time lags of 1, 2, 4 and 5 years for firm-internal knowledge and 3, 4, 7, 8 years for firm-external knowledge respectively.

Finally, like firm R&D data, data on investments in manufacturing equipment was obtained from annual reports and SEC filings. For each firm, we used the value of plants and manufacturing equipment at cost levels to determine annual changes in the equipment owned by the company. Since according to expert interviews ramping up production for PV takes around a year, we use a one-year time lag for this variable.
Controls

Controls were chosen such that they covered all important factors affecting firm-level changes in the cost and performance of PV cells. Based on a literature review and the solicitation of industry experts, public R&D, economies of scale, learning-by-doing and raw material costs were identified as crucial components (Nemet, 2006). Data on public R&D investments was obtained from the International Energy Agency’s “Energy technology research and development” database which contains data on public R&D in PV for 15 OECD countries since 1975. The data contained in this database covers approximately 80 to 90% of the global public R&D investments in recent years (Breyer et al., 2010). Similar to private R&D, annual values for public R&D investments were cumulated to build knowledge stocks under the assumption of depreciation rates ranging from 0% to 40% and time lags of 3 to 8 years. To measure economies of scale we use annual data on the firm’s cell production capacity in MW (Stigler, 1958). Learning-by-doing was operationalized using cumulative cell production in MW over time (Arrow, 1962b). Data for both cell production and production capacity was obtained from the firm’s annual reports as well as the PV industry magazine Photon which conducts an annual survey of production data. Like for the knowledge stocks from R&D, for each firm we built several production stocks with different rates of depreciation ranging from 0% to 40%. Both, cell production and cell production capacity were included in the model using a time lag of 1 year. We chose this time lag based on closer review of production data which indicated that it takes around a year for a company after installing production equipment for it to operate at maximum capacity and efficiency.

The most important raw material that serves as an input into PV cells is crystalline silicon. The prices of silicon have strongly fluctuated over the last years which has had a considerable effect on the cost of PV cells (Hoppmann et al., 2013). As a control in our model, we therefore included data on silicon prices obtained from Bloomberg. Companies purchase silicon both through longer-term contracts and on the spot market. Since the exact ratio between these two sources of silicon is unknown for the single companies, in our model we assumed a ratio of 1:1 for all companies, which according to industry experts, is a reasonable assumption. Like costs of PV cells and R&D, silicon prices were expressed in 2008 prices.

Besides the aforementioned factors, we controlled for the firms’ vertical integration by including dummies for value chain steps other than cell production, i.e., silicon production, ingot production, wafer production and module production, over time. This data was extracted from annual reports and SEC filings. Since our calculations are done in USD but almost all firms are located outside the US, costs are also influenced by the USD exchange rate. We control for this factor by including average annual exchange rates over time obtained from OANDA (2012). To account for
unobserved, time-specific factors, such as economic conditions, we also tried including time dummies. However, since time dummies were neither individually nor jointly significant, they were subsequently dropped.

Finally, costs in PV cells might also be driven by advancements in other industries or input from users (Von Hippel, 2009). In fact, the wafer-based crystalline PV has strongly benefited from the semiconductor industry in the 1970s and 1980s (Nemet, 2006). However, our study is limited to the years 2000 to 2011 during which a strong PV industry with relatively mature products had emerged that mainly develops and draws on its own knowledge. For example, Braun et al. (2010) assess cross-industry knowledge flows in the PV industry and find no significant effect. Similarly, while plant operators have played an important role in advancing other environmental technologies such as wind power (Garud and Karnøe, 2003), they have been shown to play a minor role in PV (Nemet, 2006). To avoid over-specifying our model, we therefore forego including controls for inter-industry knowledge flows and product use.

4.3 Estimation Procedure

To estimate our model, we use panel data regression analysis. A Hausman test rejected the null hypothesis of random effects. Consequently, we use a model including firm-fixed effects which capture firm characteristics that are constant over time. We started with a model that regresses our independent variable on controls and firm knowledge (model 1) and subsequently added our independent variables pertaining to knowledge spillovers (models 2 and 3). Since the controls ‘firm cell production’ and ‘firm cell production capacity’ turned out to be highly correlated ($r = 0.92$; see Table 1), we tested two different model specifications (models a and b), including only one of these variables at a time. This procedure is common in the literature which has argued that economies of scale and learning-by-doing are strongly related and has even subsumed the latter effect under the former (Scherer, 1996, Dutton and Thomas, 1984). Moreover, the knowledge stock from public R&D shows a rather high correlation with the stock of knowledge for other firms in the industry ($r = 0.76$). Apart from a model that includes the knowledge stock from public R&D, we therefore also tested a model without this control variable (model c). To test hypotheses 3a and b, we included an interaction term of firm-internal R&D stock and the knowledge stock from other firms and public R&D respectively (models 4 and 5). To account for diminishing returns (Griliches, 1998) and bring our data closer to normal form, all variables except for the dummies are included in logarithmic form. Moreover, throughout our model we used autocorrelation and heteroscedasticity robust estimation techniques.
A common problem encountered in regression analyses is the one of endogeneity (Antonakis et al., 2010). In our model, the concern for reverse causality is alleviated by the fact that for all variables except dummies, silicon prices and USD exchange rate we make use of time lags. Still, R&D investments of firms might be influenced by expectations regarding the future development of the performance-to-cost ratio, thereby causing standard errors to be biased. While this effect is likely to be observed in many industries, there is strong evidence that it is very small in the PV industry since both the development of revenues as one of the main determinants of R&D investments and the development of performance-to-cost ratios has been extremely volatile and uncertain (Hoppmann et al., 2013). This uncertainty is mainly due to the fact that the industry is strongly driven by policy support which changes demand in an unpredictable way. Given the high uncertainty and the rather long time lags we use, we have good reasons to assume that the actual performance-to-cost ratio observed is unlikely to have a significant effect on R&D investments three years earlier.
Table 1: Descriptive Statistics

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Mean</th>
<th>Std. Dev</th>
<th>Min</th>
<th>Max</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Cost-to-performance ratio</td>
<td>171</td>
<td>5.31</td>
<td>0.60</td>
<td>3.72</td>
<td>7.76</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Knowledge stock other firms</td>
<td>276</td>
<td>22.55</td>
<td>0.52</td>
<td>21.69</td>
<td>23.40</td>
<td>-0.56</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Knowledge stock public R&amp;D</td>
<td>276</td>
<td>21.24</td>
<td>0.05</td>
<td>21.20</td>
<td>21.36</td>
<td>-0.61</td>
<td>0.76</td>
<td>1.00</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>4 Firm knowledge stock</td>
<td>276</td>
<td>7.12</td>
<td>0.40</td>
<td>0</td>
<td>18.24</td>
<td>-0.24</td>
<td>0.62</td>
<td>0.50</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>5 Firm cell production</td>
<td>276</td>
<td>10.64</td>
<td>8.92</td>
<td>0</td>
<td>21.74</td>
<td>-0.43</td>
<td>0.49</td>
<td>0.36</td>
<td>0.45</td>
<td>1.00</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Firm cell production capacity</td>
<td>276</td>
<td>10.69</td>
<td>9.08</td>
<td>0</td>
<td>21.47</td>
<td>-0.36</td>
<td>0.52</td>
<td>0.33</td>
<td>0.44</td>
<td>0.92</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>7 Silicon production</td>
<td>271</td>
<td>0.11</td>
<td>0.31</td>
<td>0</td>
<td>-0.37</td>
<td>0.20</td>
<td>0.22</td>
<td>0.20</td>
<td>0.04</td>
<td>0.01</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Ingot production</td>
<td>271</td>
<td>0.23</td>
<td>0.42</td>
<td>0</td>
<td>-0.33</td>
<td>0.33</td>
<td>0.29</td>
<td>0.17</td>
<td>0.09</td>
<td>0.07</td>
<td>0.43</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Wafer production</td>
<td>271</td>
<td>0.33</td>
<td>0.47</td>
<td>0</td>
<td>-0.12</td>
<td>0.27</td>
<td>0.19</td>
<td>0.39</td>
<td>0.12</td>
<td>0.15</td>
<td>0.29</td>
<td>0.70</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 Module production</td>
<td>271</td>
<td>0.49</td>
<td>0.50</td>
<td>0</td>
<td>0.02</td>
<td>0.27</td>
<td>0.27</td>
<td>0.34</td>
<td>-0.03</td>
<td>-0.01</td>
<td>0.14</td>
<td>0.35</td>
<td>0.39</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 Silicon price</td>
<td>276</td>
<td>8.86</td>
<td>0.58</td>
<td>8.08</td>
<td>10.00</td>
<td>0.24</td>
<td>0.18</td>
<td>-0.42</td>
<td>0.11</td>
<td>0.12</td>
<td>0.16</td>
<td>-0.09</td>
<td>0.03</td>
<td>0.10</td>
<td>-0.09</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>12 USD exchange rate</td>
<td>276</td>
<td>-1.16</td>
<td>1.48</td>
<td>-3.54</td>
<td>0.38</td>
<td>-0.33</td>
<td>-0.13</td>
<td>-0.10</td>
<td>0.09</td>
<td>-0.13</td>
<td>-0.10</td>
<td>-0.09</td>
<td>-0.10</td>
<td>-0.01</td>
<td>0.33</td>
<td>-0.05</td>
<td>1.00</td>
</tr>
</tbody>
</table>
4 Results

Table 2 presents the results for the first three models of our panel data regression analysis in which we include cumulative cell production and the knowledge stock from public R&D as a control. The three models that control for production capacity instead of cumulative production are contained in Table A.2. The models that do not include the knowledge stock from public R&D are shown in Table A.3. In the following, we discuss the results against the background of our hypotheses derived in section 2.

Hypothesis 1a suggested that knowledge developed by other firms in an industry has a positive effect on innovation in a firm’s environmental technology. Model 2a provides clear support for this hypothesis. The coefficient describing the effect of other firms’ knowledge on the cost-to-performance ratio is negative and significant (p > 0.001), implying that a rise in the knowledge of other firms contributes to innovation in a firm’s technology. At the same time, model 2a does not provide support for hypothesis 1b which asserted that the marginal effect of knowledge developed by other firms in an industry should be smaller than the effect of the knowledge developed by the firm itself. In a model that does not include knowledge stocks from public R&D and other firms, firm knowledge has a significant effect on the cost-to-performance ratio of its products (see model 1b in Table A.3 in the appendix). However, this is not the case when adding the knowledge stocks from R&D of other firms and public R&D. Since the fit of the models that include the external knowledge stocks is significantly better, this indicates that knowledge developed by other companies plays a more important role for firms than internally developed knowledge.

At the first glance, the coefficients of knowledge developed by other firms and through public R&D in models 2a and 3a may appear rather large and those of the interaction terms very small. However, it should be kept in mind that all variables in our model, except for dummies, are in logarithmic form. The coefficients of the knowledge stock of other firms in the industry and public R&D can thus be roughly interpreted as the percentage change in the cost-to-performance ratio of the firm’s product as a result of raising the stocks by one percent. Since for the time of investigation, the knowledge stocks are large, lowering the cost-to-performance ratio through external R&D would require considerable investments. For example, the average cell cost of firms in 2011 amounted to 1.04 USD/Wp. According to our model results, lowering this cost by 0.01 USD/Wp in 2011 would have required investments in the knowledge stock by other firms of USD 469M. The coefficients of the interaction terms describe by how much the marginal effect of external knowledge spillovers on the cost-to-performance ratio of the firm’s product changes if the firm raises its firm-internal knowledge stock or investments in manufacturing by one percent. While the interaction term for investments in manufacturing equipment appears low, it should be kept in
mind that, in contrast to the knowledge stock, investments in manufacturing are measured as an annual flow variable. As a result, raising this variable by one percent will be much easier for a firm to accomplish than raising the existing knowledge stock from R&D by the same amount.

Table 2: Results of regression analyses
(dependent variable: cost-to-performance ratio of product)

<table>
<thead>
<tr>
<th></th>
<th>Model 1a: Controls</th>
<th>Model 2a: Knowledge Spillovers</th>
<th>Model 3a: Interaction Spillovers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firm knowledge stock</td>
<td>-0.0019 (1.3973)</td>
<td>0.0020 (0.0067)</td>
<td>0.9733** (0.4045)</td>
</tr>
<tr>
<td>Firm cell production</td>
<td>-0.0268*** (0.0070)</td>
<td>-0.0126** (0.0046)</td>
<td>-0.0045 (0.0045)</td>
</tr>
<tr>
<td>Silicon production (dummy)</td>
<td>-0.1719** (0.0855)</td>
<td>-0.1529 (0.0927)</td>
<td>-0.0992 (0.0780)</td>
</tr>
<tr>
<td>Ingot production (dummy)</td>
<td>-0.1337 (0.1701)</td>
<td>0.0407 (0.1485)</td>
<td>0.0019 (0.1312)</td>
</tr>
<tr>
<td>Wafer production (dummy)</td>
<td>0.0384 (0.1484)</td>
<td>0.0858 (0.1308)</td>
<td>0.0676 (0.1302)</td>
</tr>
<tr>
<td>Module production (dummy)</td>
<td>-0.0100 (0.0911)</td>
<td>0.1457 (0.1100)</td>
<td>0.1525 (0.1035)</td>
</tr>
<tr>
<td>Knowledge stock public R&amp;D</td>
<td>-5.3392*** (1.3973)</td>
<td>0.6350 (2.3541)</td>
<td>3.2298* (1.5799)</td>
</tr>
<tr>
<td>Silicon price</td>
<td>0.0573 (0.1060)</td>
<td>0.3369*** (0.1115)</td>
<td>0.3900*** (0.0730)</td>
</tr>
<tr>
<td>USD exchange rate</td>
<td>-0.5054 (0.7060)</td>
<td>1.4316*** (0.6248)</td>
<td>1.2346** (0.4618)</td>
</tr>
<tr>
<td>Knowledge stock other firms</td>
<td>-1.0686*** (0.3545)</td>
<td>-0.7734** (0.3269)</td>
<td></td>
</tr>
<tr>
<td>Knowledge stock other firms x</td>
<td>-0.0432**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Firm knowledge stock</td>
<td>(0.0180)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knowledge stock other firms x</td>
<td>-0.0005**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Firm equipment investment</td>
<td></td>
<td>(0.0002)</td>
<td></td>
</tr>
<tr>
<td>R² within</td>
<td>0.6385</td>
<td>0.7119</td>
<td>0.7528</td>
</tr>
<tr>
<td>ΔF</td>
<td>9.69***</td>
<td>16.57***</td>
<td></td>
</tr>
<tr>
<td>Observations</td>
<td>171</td>
<td>171</td>
<td>166</td>
</tr>
</tbody>
</table>

* p<0.1, ** p<0.05, *** p<0.01
Model 3a and 3b finally test our hypotheses 2a and 2b which state that a firm’s own knowledge and investments in manufacturing equipment should positively moderate the degree to which firm-external knowledge from other firms affects the cost-to-performance ratio of its products. Interaction terms for both variables are negative and significant, implying that in fact, firm-internal knowledge and investments in manufacturing equipment positively moderate the absorption of knowledge from other firms in the industry. All results obtained in models 1a to 3a hold when substituting cumulative cell production as a control with production capacity (see Table A.2). When dropping the knowledge stock from public R&D as a control, however, the interaction between firm’s own knowledge and knowledge of other firms loses its significance (see Table A.3). Moreover, the results are fairly robust against changes in knowledge depreciation and lags (see Tables A.4 and A.5 in the appendix). Except for low assumed depreciation of knowledge in public R&D, the coefficient for knowledge spillovers from other firms remains significant in all cases. Similarly, the interaction term for knowledge from other firms and investments in manufacturing almost never becomes insignificant. Findings for the term describing the interaction between the knowledge from other firms and the firm’s own knowledge are less robust. The effect for this term becomes insignificant for lower assumed depreciation rates and higher lags of knowledge from other firms as well as lower assumed depreciation rates and smaller lags of public R&D. Table 3 summarizes the outcome of our hypothesis tests.

Table 3: Summary of hypothesis tests

<table>
<thead>
<tr>
<th>No.</th>
<th>Hypothesis</th>
<th>Supported?</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1 a)</td>
<td>Knowledge developed by other firms in an industry has a positive effect on innovation in a firm’s environmental technology.</td>
<td>Yes</td>
</tr>
<tr>
<td>H1 b)</td>
<td>Knowledge developed by other firms in an industry has a smaller marginal effect on innovation in a firm’s environmental technology than the knowledge developed by the firm itself.</td>
<td>No</td>
</tr>
<tr>
<td>H2 a)</td>
<td>The effect of knowledge developed by other firms in an industry on innovation in a firm’s environmental technology is positively moderated by the knowledge developed by the firm itself.</td>
<td>(Yes)</td>
</tr>
<tr>
<td>H2 b)</td>
<td>The effect of knowledge developed by other firms in an industry on innovation in a firm’s environmental technology is positively moderated by the firm’s investment in manufacturing equipment.</td>
<td>Yes</td>
</tr>
</tbody>
</table>
5 Discussion

In the following, we discuss the implications of our results. We begin by providing possible explanations for the findings presented in Section 5.1. Based upon this, in Section 5.2 and 5.3 we then detail how our study contributes to the existing literature and how it might help informing practical decision-making of both managers and policy-makers. Finally, we outline the most important limitations of our study and make suggestions for future research in Section 5.4.

5.1 R&D and Knowledge Spillovers in the PV Industry

From our hypothesis tests presented in Section 4, three major questions arise which require further discussion: 1) Why does knowledge developed from firm-internal R&D significantly affect a firm’s cost-to-performance ratio only indirectly through knowledge absorption and 2) why do investments in manufacturing equipment facilitate knowledge spillovers from other firms producing wafer-based c-Si PV cells?

We provide three main explanations for our finding that knowledge developed from firm-internal R&D does not directly affect the cost-to-performance ratio of a firm’s PV cells. First, this result may, at least partly, be due to our sample size and the lack of a clear convention of which funds are reported as R&D. Second a plausible explanation lies in the fact that we measure the innovative outcome of R&D with regard to wafer-based crystalline PV, i.e., one specific PV technology. While all companies in our sample strongly focus on producing this technology, several of them simultaneously explore alternative PV technologies, such as thin-film PV or emerging PV concepts. The costs for this exploration activity are included in the R&D data we use to build the knowledge stock.\(^1\) However, since the alternative PV concepts differ from wafer-based c-Si, these investments have a smaller impact on the cost-to-performance ratio of the latter technology which may provide some explanation for why we do not measure a significant effect of firm-internal R&D. Third, and most importantly, R&D investments in the PV industry may mainly serve as an absorption mechanism. As discussed in Section 3, the PV industry is growing at an extremely fast pace, resulting in a strong expansion of knowledge on wafer-based crystalline PV technologies. It seems plausible that in such a situation the focus of firm R&D might be on integrating external knowledge rather than leveraging own knowledge sources. This might explain why we find R&D to be

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\(^1\) Unfortunately, a break-down of R&D expenditures according to PV technologies is not publicly available. Statements in annual reports and the patent portfolio of companies, however, indicate that several companies, such as Arise, Bosch, Q-Cells, Renewable Energy Corp., Solon, Sunpower, Suntech, Yingli have invested funds into research on technologies other than wafer-based PV.
important in facilitating external knowledge while not having a direct, significant effect on the cost-to-performance ratio of a firm’s PV cells.

The finding that investments in manufacturing equipment positively moderate the knowledge spillovers from other firms lends support to our hypothesis that in the PV industry equipment manufacturers have played an important role in enabling knowledge transfer between firms. As discussed in Section 3, previous studies have provided anecdotal evidence that equipment manufacturers in the PV industry have integrated knowledge into their products that has been gained in collaboration with German and US manufacturers of PV cells. By purchasing equipment from the equipment manufacturers, especially Chinese and Taiwanese companies have been able to draw on this knowledge and manufacture high-quality low-cost goods. Overall, thereby investment in equipment manufacturing appears to have served as a channel of knowledge absorption that worked in parallel to investments in R&D.

5.2 Implications for Literature

By investigating the role of knowledge spillovers in the solar photovoltaic industry, our study makes important contributions to the literature on environmental innovation and absorptive capacity. As pointed out in Section 1, at present the literature often explicitly or implicitly assumes that proactively investing in innovation for environmental technology will raise the competitiveness of companies and countries. We challenge this view by presenting evidence for inter-firm knowledge spillovers which are likely to have a strong impact on the relationship between environmental innovation and competitive advantage. On the one hand, in the presence of strong knowledge spillovers, putting in place strict environmental regulations as suggested by the Porter hypothesis might in fact quickly generate a competitive advantage. On the other hand, a competitive advantage in the presence of strong knowledge spillovers is also likely to erode very quickly. Given the strong competition in increasingly global markets, the key question to be asked when investigating the benefits of environmental innovation therefore is not if innovation can lead to competitive advantages but how such advantages can be retained over a longer period of time. Although the idea that resources underlying corporate strategies need to be inimitable to generate a lasting competitive advantage have long been pointed out in the literature dealing with the resource-based view of the firm, they have found insufficient consideration in the literature on environmental innovation. Our study shows that, in fact, investigating the relationship between environmental innovation and competitive advantage requires a profound understanding of the

2 In the presence of strong knowledge spillovers the costs firms face as a result of strict environmental regulation may in fact be much lower than is often assumed.
channels through which firms in an industry absorb and dissipate knowledge as well as the mechanisms they use to protect their intellectual property. We argue that therefore, when trying to deepen our understanding of whether, when and how environmental innovation might contribute to a competitive advantage of firms, the literature on environmental innovation can significantly benefit from a closer integration with existing streams of literature such as the knowledge-based or the resource-based view of the firm.

As a second contribution, our study highlights investments in production equipment as an important channel of absorptive capacity. Currently, the literature predominantly suggests that to identify, decode and exploit external knowledge firms need to conduct R&D. This view is based on the observation that knowledge is often highly contextual, requiring technological expertise and financial investments for a firm to benefit from it. Not surprisingly, many studies have therefore focused on processes within R&D departments, R&D collaborations and turnover of research personnel when studying a firm’s absorptive capacity.

Our findings suggest that studies focusing solely on R&D may draw an incomplete picture of a firm’s absorptive capacity. As described in the previous section, in the case of the PV industry, an important channel of knowledge transfer has been the investment in standardized production equipment. Production equipment generally embodies considerable knowledge generated during the production of a good. When developing the machinery, equipment manufacturers identify the knowledge relevant in the production process, decode it and integrate it into their products. As a result, firms buying production equipment are usually able to reap many of the benefits of external knowledge without having to make large investments in R&D. In this sense, in line with the general idea that firms can make or buy, investments in machinery serve as an alternative way of absorbing external knowledge.

Arguably, the degree to which standardized production equipment is available differs between industries (Pavitt, 1984). Generally, however, it seems reasonable to assume that with technological advancement and increasing automation of production processes, turn-key manufacturing equipment is going to play a more prominent role in many industries in the future. In fact, it has been shown that especially as markets for technologies grow and patterns of technological change become more predictable, firms tend to increasingly outsource the development of process technology (Cesaroni, 2004). Lim (2009) points out that therefore in later stages of an industry where much of the knowledge is embedded in tools and processes firms need to take a different approach towards R&D management and collaboration. We go beyond Lim (2009) in proposing that when knowledge is strongly embedded in machinery, R&D may in fact play a subordinate role for a firm’s knowledge absorption compared to investments in production equipment. Given that
turn-key manufacturing equipment presents a powerful mechanism for quickly integrating large amounts of external knowledge, competitive dynamics are likely to look very different in a market which predominantly operates on this mechanism of knowledge absorption. Taking a closer look at the role of production equipment therefore bears the potential of generating interesting new insights that complement our existing knowledge about the effects of absorptive capacity on firm performance.

5.3 Implications for Practitioners

Besides contributing to the literature on environmental innovation and absorptive capacity, our research has important implications for both corporate managers and policy makers. First, our results suggest that managers interested in generating a longer-term competitive advantage are well advised to systematically think about knowledge spillovers. Managers need to ensure that not only does their firm constantly generate innovative products but that the innovations it generates are also protected against being easily imitated by others. The literature on “open innovation” generally stresses the benefits for firms when entering into research collaborations to draw on outside knowledge. Our findings indicate that such collaborations, while often useful, also bear great risks. If not sufficiently protected, proprietary knowledge shared with partners can flow to (future) competitors in a variety of ways. Managers might therefore consider systematically mapping the channels through which knowledge flows out of their firm. Besides being useful for determining a firm’s IP protection strategy and alliances, the possibility to protect knowledge should be a critical factor taken into account when planning a firm’s technology and innovation portfolio. While in many firms knowledge protection is already a key concern, the PV industry provides a good example that the risk of knowledge spillovers is often underestimated and not managed in a strategic way.

Second, our finding that knowledge spillovers may importantly influence firm-level innovation represents both good and bad news for policy makers wishing to foster innovation in environmental technologies. On the positive side, strong knowledge spillovers raise the effectiveness of policy interventions since any policy measure that induces innovation simultaneously does so in a larger number of companies. In this sense, knowledge spillovers in the case of environmental technologies can be considered desirable from a societal perspective. On the negative side, however, knowledge spillovers also lower the possibility that fostering innovation in a particular technology will only benefit domestic firms. Policy makers interested in raising the competitiveness of their country might therefore design policy interventions in a way that knowledge spillovers remain limited to domestic companies. One way of limiting knowledge spillovers lies in encouraging firms to protect their IP.
Yet, this measure is likely to not only limit spillovers to foreign firms but also within the country. Alternatively, policy makers may choose the industry to be supported such that it relies more strongly on tacit knowledge since these industries are more likely to experience locally bounded spillovers. Overall, if many governments value the support of domestic industries higher than the broad diffusion of innovations, such strategies bear the risk of severely hampering innovative activity in environmental technologies in the longer run. Overall, therefore, policy makers face a trade-off between most effectively advancing environmental innovation and inducing growth in domestic industries.

5.4 Limitations and Future Research

Our study has several limitations which lend themselves as avenues for future research. First, in our analysis we present qualitative evidence that manufacturing equipment served as an important channel of knowledge spillovers. However, our analysis is limited to a particular industry. Based on theoretical considerations, we would expect investments in equipment to serve as an important channel of absorptive capacity in a large and increasing number of industries. To test this proposition, we recommend that future research explicitly compare the prevalence and effect of the various channels of knowledge spillovers in different empirical settings.

Second, an important question to ask is to which extent our findings are generalizable to environmental technologies other than wafer-based crystalline PV. Given the various channels through which knowledge can flow and their increasing availability over time, we would expect knowledge spillovers to play an important role in other environmental technologies. At the same time, however, environmental technologies may differ considerably in the degree to which they depend on specific channels of knowledge transfer (Huenteler et al., 2012). These channels through which knowledge spills over in turn are likely to determine whether and how this knowledge can be accessed by other firms (Teece, 1998). Future studies might therefore take a closer look at differences in knowledge spillovers between different environmental technologies and investigate how these are related to competitive dynamics in the respective field.

Finally, while in the literature it has been pointed out that knowledge spillovers depend on geographic proximity (Audretsch and Feldman, 1996), in our analysis we were not able to control for this factor as we lacked data on public R&D for several countries included in our analysis, e.g., China, and a breakdown of industry R&D investments according to geography was not available. Given that the PV industry is a global industry and the main mechanisms driving spillovers – such as sales of turn-key manufacturing equipment – act on an international level, we consider the findings of our analysis to paint an accurate picture of spillovers for PV. Yet, especially when
extending our analysis to other environmental technologies, spillovers may be of a more localized nature, requiring researchers to make use of spatially disaggregated measures of geographic proximity, e.g., by drawing on patents rather than R&D investments as a proxy for knowledge. The geographic scope of spillovers plays an important role when trying to explain to what extent innovation triggered by domestic policies may benefit firms in a particular country vs. the industry as a whole. Therefore, we see much value in studying the role of geographic proximity as a factor that moderates the effect of different forms of knowledge spillovers.

6 Conclusion

In this paper we investigated the role of knowledge spillovers for firm-level innovation in environmental technologies. Previous research demonstrated that knowledge possessed by a firm may leak to competitors through a variety of channels. Although such knowledge spillovers may have important consequences for the degree to which firms are able to appropriate the benefits of innovation and generate a longer-term competitive advantage, currently inter-firm knowledge spillovers have received little attention in the literature on environmental innovation. To address this gap, we used panel data regression to analyze data from 23 publicly listed pure-play manufacturers of wafer-based crystalline PV cells from 2000 to 2011. We find evidence that innovation in PV cells is driven by knowledge spillovers from other firms in the industry. In line with the literature on absorptive capacity, we find that knowledge spillovers are positively moderated by the firm’s own prior knowledge. More interestingly, however, we also provide evidence that investments in manufacturing equipment have facilitated knowledge spillovers. When developing turn-key production equipment manufacturers draw on knowledge from producers, integrate it into their products and sell these to competitors who are thus able to quickly absorb considerable amounts of knowledge without having to make large investments in R&D. We argue that a better understanding of the channels through which knowledge is transferred between companies is of critical importance if one is to understand the relationship between environmental innovation and a competitive advantage of firms or countries. Furthermore, by pointing to investments in manufacturing equipment as a facilitator of knowledge transfer our study highlights a potentially important channel of absorptive capacity which so far has received little attention in the literature. We argue that corporate managers have much to gain by systematically mapping and considering knowledge spillovers when devising technology strategies. For policy makers, fostering environmental technologies involves a trade-off between encouraging knowledge spillovers to raise the overall effectiveness of policy interventions and limiting them to support the development of domestic industries.
References


# Appendix

Table A.1: Sample (data from Photon, 2012)

<table>
<thead>
<tr>
<th>No.</th>
<th>Issue Category</th>
<th>Country</th>
<th>Production 2011</th>
<th>Production Share 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Arise Technologies</td>
<td>CAN</td>
<td>17 MW</td>
<td>0.0%</td>
</tr>
<tr>
<td>2</td>
<td>Bosch Solar Energy (incl. Ersol Solar)</td>
<td>GER</td>
<td>450 MW</td>
<td>1.2%</td>
</tr>
<tr>
<td>3</td>
<td>Canadian Solar</td>
<td>CAN</td>
<td>1,010 MW</td>
<td>2.7%</td>
</tr>
<tr>
<td>4</td>
<td>China Sunergy Co. Ltd. ADS</td>
<td>CN</td>
<td>440 MW</td>
<td>1.2%</td>
</tr>
<tr>
<td>5</td>
<td>DelSolar</td>
<td>TW</td>
<td>410 MW</td>
<td>1.1%</td>
</tr>
<tr>
<td>6</td>
<td>E-Ton Solar</td>
<td>TW</td>
<td>290 MW</td>
<td>0.5%</td>
</tr>
<tr>
<td>7</td>
<td>Evergreen Solar Inc.</td>
<td>US</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>Gintech Energy</td>
<td>TW</td>
<td>873 MW</td>
<td>2.3%</td>
</tr>
<tr>
<td>9</td>
<td>Hanwha SolarOne</td>
<td>CN</td>
<td>815 MW</td>
<td>2.2%</td>
</tr>
<tr>
<td>10</td>
<td>JA Solar</td>
<td>CN</td>
<td>1,700 MW</td>
<td>4.6%</td>
</tr>
<tr>
<td>11</td>
<td>Jinkosolar Holding Co</td>
<td>CN</td>
<td>740 MW</td>
<td>2.0%</td>
</tr>
<tr>
<td>12</td>
<td>LDK Solar</td>
<td>CN</td>
<td>680 MW</td>
<td>1.8%</td>
</tr>
<tr>
<td>13</td>
<td>Motech Industries</td>
<td>TW</td>
<td>1,100 MW</td>
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<td>14</td>
<td>Neo Solar Power</td>
<td>TW</td>
<td>890 MW</td>
<td>2.2%</td>
</tr>
<tr>
<td>15</td>
<td>Q-Cells SE</td>
<td>GER</td>
<td>717 MW</td>
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</tr>
<tr>
<td>16</td>
<td>Renewable Energy Corp.</td>
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<td>730 MW</td>
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</tr>
<tr>
<td>17</td>
<td>Solarfabrik AG</td>
<td>GER</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>18</td>
<td>Solon SE</td>
<td>GER</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>19</td>
<td>SunPower Corporation</td>
<td>US</td>
<td>922 MW</td>
<td>2.5%</td>
</tr>
<tr>
<td>20</td>
<td>Suntech Power Holdings Co., Ltd.</td>
<td>CN</td>
<td>2,220 MW</td>
<td>6.0%</td>
</tr>
<tr>
<td>21</td>
<td>Sunways</td>
<td>GER</td>
<td>62 MW</td>
<td>0.2%</td>
</tr>
<tr>
<td>22</td>
<td>Trina Solar Limited</td>
<td>CN</td>
<td>1,550 MW</td>
<td>4.2%</td>
</tr>
<tr>
<td>23</td>
<td>Yingli Green Energy Holding Co., Ltd.</td>
<td>CN</td>
<td>1,604 MW</td>
<td>4.3%</td>
</tr>
<tr>
<td>SUM</td>
<td>2419</td>
<td></td>
<td>17,040 MW</td>
<td>45.8%</td>
</tr>
</tbody>
</table>
Table A.2: Results of regression analyses for models using cell production capacity instead of cell production as control variable (dependent variable: cost-to-performance ratio of product)

<table>
<thead>
<tr>
<th></th>
<th>Model 1b: Controls</th>
<th>Model 2b: Knowledge Spillovers</th>
<th>Model 3b: Interaction Terms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firm knowledge stock</td>
<td>-0.0047 (0.0087)</td>
<td>0.0000 (0.0069)</td>
<td>1.0031** (0.3825)</td>
</tr>
<tr>
<td>Firm cell production capacity</td>
<td>-0.0181** (0.0067)</td>
<td>-0.0038 (0.0056)</td>
<td>-0.0018 (0.0052)</td>
</tr>
<tr>
<td>Silicon production</td>
<td>-0.1829** (0.0778)</td>
<td>-0.1531 (0.1079)</td>
<td>-0.4030 (0.0703)</td>
</tr>
<tr>
<td>(dummy)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ingot production (dummy)</td>
<td>-0.1123 (0.1728)</td>
<td>0.0173 (0.1500)</td>
<td>0.0115 (0.1317)</td>
</tr>
<tr>
<td>Wafer production (dummy)</td>
<td>0.0279 (0.1519)</td>
<td>0.0779 (0.1313)</td>
<td>0.0651 (0.1309)</td>
</tr>
<tr>
<td>Module production (dummy)</td>
<td>0.0198 (0.0980)</td>
<td>0.1689 (0.1118)</td>
<td>0.1632 (0.1016)</td>
</tr>
<tr>
<td>Knowledge stock public R&amp;D</td>
<td>-5.9367** (1.5079)</td>
<td>-0.8477 (2.4813)</td>
<td>3.5420** (1.5961)</td>
</tr>
<tr>
<td>Silicon price</td>
<td>0.0294 (0.1169)</td>
<td>0.3459*** (0.1145)</td>
<td>0.4030*** (0.1016)</td>
</tr>
<tr>
<td>USD exchange rate</td>
<td>0.8539 (0.8142)</td>
<td>1.6369 (0.6721)</td>
<td>1.2962** (0.4696)</td>
</tr>
<tr>
<td>Knowledge stock other firms</td>
<td>-1.1786*** (0.3625)</td>
<td>-0.8324** (0.3013)</td>
<td></td>
</tr>
<tr>
<td>Knowledge stock other firms x Firm knowledge stock</td>
<td>-0.0445** (0.0170)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knowledge stock public R&amp;D x Firm equipment investment</td>
<td>-0.0006*** (0.0002)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R² within</td>
<td>0.6151</td>
<td>0.7026</td>
<td>0.7521</td>
</tr>
<tr>
<td>ΔF</td>
<td>10.57***</td>
<td>24.69***</td>
<td></td>
</tr>
<tr>
<td>Observations</td>
<td>171</td>
<td>171</td>
<td>166</td>
</tr>
</tbody>
</table>

* p<0.1, ** p<0.05, *** p<0.01
Table A.3: Results of regression analyses for models without knowledge stock from public R&D as control variable (dependent variable: cost-to-performance ratio of product)

<table>
<thead>
<tr>
<th></th>
<th>Model 1c: Controls</th>
<th>Model 2c: Knowledge Spillovers</th>
<th>Model 3c: Interaction Terms</th>
</tr>
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<tbody>
<tr>
<td>Firm knowledge stock</td>
<td>-0.1818***</td>
<td>0.0025</td>
<td>0.6482</td>
</tr>
<tr>
<td></td>
<td>(0.0056)</td>
<td>(0.0071)</td>
<td>(0.4545)</td>
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<tr>
<td>Firm cell production</td>
<td>-0.0369***</td>
<td>-0.0131***</td>
<td>-0.0071</td>
</tr>
<tr>
<td></td>
<td>(0.0083)</td>
<td>(0.0040)</td>
<td>(0.0044)</td>
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<tr>
<td>Silicon production (dummy)</td>
<td>-0.2684***</td>
<td>-0.1495</td>
<td>-0.0919</td>
</tr>
<tr>
<td></td>
<td>(0.1137)</td>
<td>(0.0948)</td>
<td>(0.0821)</td>
</tr>
<tr>
<td>Ingot production (dummy)</td>
<td>-0.0259</td>
<td>0.0518</td>
<td>0.0461</td>
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<tr>
<td></td>
<td>(0.1787)</td>
<td>(0.1418)</td>
<td>(0.1328)</td>
</tr>
<tr>
<td>Wafer production (dummy)</td>
<td>0.0397</td>
<td>0.0827</td>
<td>0.0540</td>
</tr>
<tr>
<td></td>
<td>(0.1996)</td>
<td>(0.1260)</td>
<td>(0.1240)</td>
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<tr>
<td>Module production (dummy)</td>
<td>-0.0690</td>
<td>0.1409</td>
<td>0.1172</td>
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<td></td>
<td>(0.0807)</td>
<td>(0.1077)</td>
<td>(0.1042)</td>
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<tr>
<td>Silicon price</td>
<td>0.3219***</td>
<td>0.3065***</td>
<td>0.2573***</td>
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<td></td>
<td>(0.0769)</td>
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<td>USD exchange rate</td>
<td>-0.2035</td>
<td>1.3975*</td>
<td>1.2100**</td>
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<td></td>
<td>(0.6998)</td>
<td>(0.6924)</td>
<td>(0.5395)</td>
</tr>
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<td>Knowledge stock other firms</td>
<td>-1.0009***</td>
<td>-0.6214**</td>
<td></td>
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<tr>
<td></td>
<td>(0.2061)</td>
<td>(0.3096)</td>
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<tr>
<td>Knowledge stock other firms x Firm knowledge stock</td>
<td>-0.0287</td>
<td>(0.0202)</td>
<td></td>
</tr>
<tr>
<td>Knowledge stock public R&amp;D x Firm equipment investment</td>
<td>-0.0004*</td>
<td>(0.0002)</td>
<td></td>
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<tr>
<td>R² within</td>
<td>0.5521</td>
<td>0.7114</td>
<td>0.7434</td>
</tr>
<tr>
<td>∆F</td>
<td>23.59***</td>
<td>12.08***</td>
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<td>Observations</td>
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* p<0.1, ** p<0.05, *** p<0.01
<table>
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<th>Depreciation Rate</th>
<th>Knowledge stock other firms</th>
<th>Firm knowledge stock</th>
<th>Knowledge other firms x Firm knowledge stock</th>
<th>Knowledge other firms x Invest manf.</th>
</tr>
</thead>
<tbody>
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<td></td>
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<td>Model 2a</td>
<td>Model 3a</td>
<td>Model 3a</td>
<td>Model 3a</td>
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<tr>
<td></td>
<td></td>
<td>Knowledge stock other firms</td>
<td>Firm knowledge stock</td>
<td>Knowledge other firms x Firm knowledge stock</td>
<td>Knowledge other firms x Invest manf.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-1.5046***</td>
<td>0.0038</td>
<td>-0.0422</td>
<td>-0.0004**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.4864)</td>
<td>(0.0071)</td>
<td>(0.0293)</td>
<td>(0.0002)</td>
</tr>
<tr>
<td></td>
<td>10%</td>
<td>-1.2133***</td>
<td>0.0030</td>
<td>-0.0413*</td>
<td>-0.0004**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.3945)</td>
<td>(0.0069)</td>
<td>(0.0213)</td>
<td>(0.0002)</td>
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<tr>
<td></td>
<td>20%</td>
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<td>0.0020</td>
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<td>-0.0005**</td>
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<tr>
<td></td>
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<td>(0.3545)</td>
<td>(0.0067)</td>
<td>(0.0180)</td>
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</tr>
<tr>
<td></td>
<td>30%</td>
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<td>0.0010</td>
<td>-0.0442**</td>
<td>-0.0005**</td>
</tr>
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<td>(0.0067)</td>
<td>(0.0167)</td>
<td>(0.0002)</td>
</tr>
<tr>
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<td>40%</td>
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<td>0.0003</td>
<td>-0.0440**</td>
<td>-0.0005**</td>
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<td>(0.3255)</td>
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<tr>
<td></td>
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<td>0% -1.4948*</td>
<td>0.0015</td>
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* p<0.1, ** p<0.05, *** p<0.01
Table A.5: Coefficients in Models 2 and 3 as a function of lags

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<th>Variable</th>
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<th>Model 3a</th>
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<td>-0.0014 (0.0062)</td>
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* p<0.1, ** p<0.05, *** p<0.01
Paper III
Compulsive Policy-Making –
The Evolution of the German Feed-in Tariff System
for Solar Photovoltaic Power

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Abstract

The technological innovation systems (TIS) approach identifies a number of functions, or key processes, policy makers should support to encourage the development and diffusion of socially desired technologies. But while the usefulness of TIS analyses in explaining the ‘success’ or ‘failure’ of innovation systems has been demonstrated in a large number of empirical settings, we still lack a detailed understanding of the dynamics at play when policy makers address systemic problems. In this paper, we show how the complexity of socio-technical systems and the uncertain nature of technological change shape the process of targeted policy interventions in TIS. Towards this end we analyzed the evolution of the German feed-in tariff (FIT) system for solar photovoltaic power, a highly effective and widely copied policy instrument targeted at ‘market formation’. We find that the policy has been subject to a considerable amount of changes which are the result of policy makers successfully responding to unexpected issues and new bottlenecks. Interestingly, however, many of these emerging issues were driven by unforeseen technological developments induced by previous policy interventions. We argue that the pattern of policy serving as both a solution to and a driver of technological bottlenecks shows strong similarities with what Rosenberg (1969) called ‘compulsive sequences’ in the development of technical systems. By shedding more light on the dynamics of policy-making in the realm of socio-technical systems, our framework represents a first step towards more closely integrating the literature on TIS with the work on policy learning and reflexive governance.

Keywords: Sustainability Transitions, Technological Innovation System, Governance of Technological Change, Policy Learning, Feed-in Tariff, Solar Photovoltaic Power
1 Introduction

Environmental degradation, resource depletion and climate change are pressing societal problems that call for a redirection of economic growth towards a more environmentally sustainable pathway (UNEP, 2011). Such a ‘sustainability transition’ is likely to require the development and use of fundamentally new products, processes and services (Smith et al., 2010). Whereas this implies an altered behavior of a wide range of actors, such as corporations and private consumers, there is a wide consensus that public policy will have to play an important part in the process of transition. Considering the urgency of problems, it is argued that regulators should guide and accelerate the process of change by altering the institutional framework, breaking path dependencies and fostering the emergence of innovative, more environmentally benign technologies (Jacobsson and Bergek, 2011, Unruh, 2002).

In recent years innovation scholars have strongly advanced our understanding of the role that public policy can play in fostering the transition towards sustainability. For example, the literature on technological innovation systems (TIS) has suggested a number of ‘functions’ or ‘key processes’ of socio-technical systems which policy makers should support in order to foster the development and diffusion of technologies (Bergek et al., 2008, Hekkert et al., 2007). These functions have proven a useful heuristic in structuring the analysis of socio-technical systems and identifying ‘system failures’ to be addressed by policy makers. Up to this point, however, we still lack a detailed understanding of the dynamics that ensue when policy makers address the identified shortcomings and engage as ‘system builders’ (Kuhlmann et al., 2010). While the literature emphasizes the complex nature of TIS, it remains unclear how this affects policy-maker’s ability to purposefully induce technological change (Faber and Alkemade, 2011). Studies in the field of policy sciences have stressed the emergent nature of policy processes but have not focused on technological change and related uncertainties as a potential driver.

To gain more insights into the dynamics that result when policy makers try to foster specific functions of a TIS, in this paper we address the question how the complex dynamics of socio-technical systems shape the process of policy interventions targeted at inducing technological change. Towards this end, we study the evolution of the widely copied German feed-in tariff (FIT) system for solar photovoltaic (PV) power as an instrument that has been highly effective in fostering ‘market formation’. In this context, we analyzed a large number of archival documents pertaining to the policy process such as legislative texts, protocols of parliamentary debates, expert studies and press articles. This archival analysis was complemented by interviews with policymakers and designated PV industry experts as actors in and observers of the policy process.
Based on an in-depth discussion of the underlying dynamics, we show that the German FIT for PV has evolved in a highly iterative way and that this development was often driven by unforeseen developments in the technological sphere. Policy makers reacted to emerging issues or ‘system failures’ by dynamically adjusting the policy design, making the German FIT for PV a good example for policy learning. However, at the same time, our analysis indicates that policy not only eliminated issues but, by inducing unexpected technological developments, simultaneously contributed to their emergence. The more momentum the TIS gained, the more the process became ‘compulsive’ in that unforeseen technological developments exerted direct pressures on policy makers to adjust the design of previously implemented policies. We argue that understanding political intervention in TIS in analogy to what Rosenberg (1969) described as ‘compulsive sequences’ of innovation, may help informing future interventions in TIS. The framework of ‘compulsive policy-making’ we propose goes beyond more generic policy frameworks (e.g., Lindblom, 1959, Voß and Kemp, 2006) by explicitly pointing to the role of complex technology dynamics as a driver of policy making.

The remainder of this paper is structured as follows: Section 2 presents a brief overview of the work on technological innovation systems and discusses potential mechanisms shaping policy dynamics suggested in the literature. Research case and method are outlined in Sections 3 and 4. Section 5 describes the evolution of the German FIT system for PV, followed by a discussion of the underlying technological dynamics and the theoretical framework we derive. Section 6 presents implications for the literature on TIS, policy learning and reflexive governance. We conclude with a brief description of the study’s limitations, suggestions for future research and a summary of the main contributions.

2 Theoretical Perspective

2.1 Functional Analysis of Technological Innovation Systems as a Means to Inform Policy Interventions

In the last two decades, a number of different approaches have been suggested to examine how policy makers can foster a ‘sustainability transition’, so as to decouple economic growth from its adverse environmental and societal impacts (for an overview, see e.g., Smith et al., 2005, Nill and Kemp, 2009, Markard et al., 2012). In this context, systemic approaches to policy making in general and the framework of ‘technological innovation systems’ (TIS) in particular have gained increasing importance (Smits and Kuhlmann, 2004, van Mierlo et al., 2010, Edquist, 2011). The TIS approach suggests that the development, diffusion and use of technologies results from the interplay of actors
(e.g., firms, policy makers), networks (formal and informal) and institutions (e.g., norms, values or standards) within a socio-technical system (Carlsson and Stankiewicz, 1991).

To assess and compare the performance of TIS, a number of ‘functions’, ‘key processes’ or ‘key activities’ have been proposed that need to be present to facilitate innovation in a particular technology (Bergek et al., 2008, Hekkert et al., 2007). For example, the taxonomy developed by Bergek et al. (2008) includes the processes of ‘knowledge development and diffusion’, ‘influence on the direction of search’, ‘entrepreneurial experimentation’, ‘market formation’, ‘legitimation’, ‘resource mobilization’ and ‘development of positive externalities’. The analysis of these functions offers a useful starting point for identifying system failures to be addressed by policy makers (Wieczorek and Hekkert, 2012). It is suggested that, to devise technology-specific policies, policy makers should measure the extent to which different functions are present within a TIS, detect mechanisms inducing or blocking the functions and implement policy measures to remove potential system bottlenecks (Bergek et al., 2008).

The functional analysis of TIS has been applied to a rich assortment of empirical cases as diverse as biomass (e.g., Negro et al., 2008), solar photovoltaics (e.g., Dewald and Truffer, 2011), wind energy (e.g., Bergek and Jacobsson, 2003), alternative transport fuels (e.g., Suurs and Hekkert, 2009) or carbon capture and storage (e.g., van Alphen et al., 2010). In this context, it has proven a powerful heuristic for identifying blocking mechanisms and explaining the success or failure of technology development and diffusion. However, since the focus of the TIS is on analyzing the socio-technical system as a whole rather than the specifics of the policy process, “the question remains […] how functions translate into policymaking and policy effects” (Kuhlmann et al., 2010, p.6). While the TIS framework itself does not claim to provide a detailed explanation of the policy process, a better understanding of the link between its functions and policy making could be fruitful as it may help to a) examine explicit or implicit assumptions underlying the TIS framework and b) improve the practical relevance of policy recommendations made. Therefore, in the following we take a closer look at two mechanisms that may affect the outcome of targeted policy interventions in TIS.

2.2 Potential Mechanisms Shaping the Dynamics of Policy Interventions in TIS

First, early studies in the field of TIS have investigated the role of politics and interest as one important mechanism linking functions and policy making (Jacobsson and Bergek, 2004, Jacobsson et al., 2004, Jacobsson and Lauber, 2006). In line with the literature on the politics of sustainability transitions it has been pointed out that the transformation of socio-technical systems is an inherently political process influenced by mindsets, framing and power struggles (Meadowcroft,
2009, Scrase and Smith, 2009, Meadowcroft, 2011, Kern, 2011). Politicians anchored in an existing regime are unlikely to show strong support for emerging technologies and may resist related political initiatives (Kern and Smith, 2008). Moreover, policy makers may hold differing opinions on what constitute the most important blocking mechanisms and how to remove them to foster a particular function (Meadowcroft, 2009).

Second, even if there is a political consensus regarding the goals and means of policy-making, interventions in TIS may be decisively influenced by the inherent complexity of socio-technical systems which may limit the degree to which consequences of policy interventions can be accurately foreseen (Faber and Alkemade, 2011). As expressed in Lindblom’s (1959) ‘science of muddling through’, policy makers are unlikely to possess the knowledge to accurately foresee all consequences of their actions. Rather, they might have to make use of a try-and-error approach to partially achieve their goals and subsequently adjust actions based on the experience they have gained (Lindblom, 1959, Lindblom, 1979, Forester, 1984). This may be particularly true when policy makers try to purposefully induce technological change which has been shown to evolve in a non-linear, unpredictable way. In line with this, the literature stresses that TIS consist of a large number of structural elements that interact through various channels, implying that the outcome of policy measures may be hard to anticipate. The literature on reflexive governance therefore stresses that policies targeted at fostering a sustainability transition need to be designed in a highly flexible and adaptive way (Voß and Kemp, 2006). Yet, while it has been acknowledged that policy interventions in TIS may have unforeseen effects (Bergek et al., 2008, Bergek and Jacobsson, 2003), the uncertainties surrounding the outcome of policy interventions have received limited attention in the literature on TIS.

Uncertainties regarding the effects of policy measures seem rather unproblematic if removing a blocking mechanism to a particular function in any case were to positively affect the performance of all other functions of TIS. In fact, at present, the literature predominantly assumes positive interdependencies between the different functions. It is suggested that fostering the concurrent presence of several functions leads to ‘virtuous cycles’ (Hekkert and Negro, 2009, Negro and Hekkert, 2008, Bergek and Jacobsson, 2003), ‘cumulative causation’ (Suurs and Hekkert, 2009, Hekkert et al., 2007) and the emergence of ‘positive externalities’ (Bergek et al., 2008). Positive interdependencies have been empirically demonstrated in several case studies (e.g., Suurs and Hekkert, 2009). Yet, one could think of cases where removing a blocking mechanism that hinders a particular function may not affect all other functions in a positive way. For example, implementing

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1 It is important to note that functions as key processes of a TIS cannot directly interact with each other. Rather, altering a function will always require a change in the structural elements of the TIS (i.e., actors, networks and institutions), which in turn affects the degree to which particular functions are present.
product standards to ‘guide the direction of search’ may hamper the scope of ‘entrepreneurial experimentation’. A similar effect could be expected if ‘market formation’ leads to the scaling-up of production and lower product costs, thereby raising the barriers to market entry for entrepreneurs (Hoppmann et al., 2013). As a result, complex interdependencies between the elements of TIS may lead to situations where policy interventions unexpectedly enhance existing or generate new blocking mechanisms. Considering this possibility, in this paper we focus on the question how the complex dynamics of socio-technical systems shape the process of policy interventions targeted at inducing technological change. Based on an in-depth case study of a policy intervention that addresses a particular function of a TIS, we derive a process model that integrates the different mechanisms presented in this section.

3 Research Case

To gain more insights into the dynamics that result when policy makers try to foster a particular function of a TIS, we study the evolution of the widely-copied German feed-in tariff (FIT) system for solar photovoltaic (PV) power from 1991 to early 2012. FITs, which grant power producers a fixed price per unit of electricity, are generally implemented to raise the share of renewable electricity in the electricity mix (Dewald and Truffer, 2011). Studying the evolution of this instrument therefore allows us to better understand the dynamics that result when policy makers try to purposefully foster ‘market formation’ as a core function of TIS.2

Germany is a suitable country for the analysis since throughout the period of analysis public and political support in Germany for renewables was rather high.3 All major political parties shared the general objective of increasing renewable energy supply, implying that political struggles revolved not so much around the goals (i.e., what to achieve) but the means (i.e., how to achieve them). Partisan politics thus played a smaller role than in other contexts. Furthermore, we chose Germany as a country since the FIT system has been very effective in increasing the share of renewable power in the electricity mix, and has served as a blueprint for FIT schemes in other countries (Ringel, 2006). Of the more than 60 countries that have introduced a FIT, Germany was the second country to adopt this instrument and up to this point has shown a remarkable continuity in its

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2 As will be seen in Section 5, motivations to implement a FIT often go beyond a mere diffusion of renewable energies and include goals such as technological innovation, creation of industries and jobs or the disruption of regimes. Yet, it seems reasonable to assume that many of the desired consequences of FITs are second-order effects following their immediate impact on ‘market formation’.

3 We focus on policies and market formation in Germany. Still, we include developments in the TIS for PV outside of Germany in our analysis, whenever they have important effects on the socio-technical system in that country.
operation (REN21, 2011). The long time horizon over which developments in the legislation can be tracked was considered advantageous for obtaining robust results.

We further confine our analysis to the case of solar photovoltaic power. While PV bears a large physical potential for the generation of clean electricity, its levelized costs of electricity (LCOE) are still well above those for fuel-based electricity sources. As a result, PV currently is strongly dependent on policy support, implying a high visibility of policy effects and policy dynamics in the socio-technical system (Peters et al., 2012). The good opportunity to observe policy dynamics in operation militates in favor of choosing PV as a unit of analysis.4

Finally, we set the temporal boundaries of our research to the time from 1991 to the beginning of 2012. We constrain our analysis to the German Renewable Energy Sources Act of 2000 and its subsequent amendments because the first version of the German FIT, the so-called ‘Stromeinspeisungsgesetz’ of 1990, had almost no direct effect on PV in Germany. The FIT of 2000 has received much attention in the years after its introduction (e.g., Jacobsson and Lauber, 2006, Jacobsson et al., 2004, Lauber and Mez, 2004), but the significant changes in the FIT scheme for PV, especially since 2007, have not yet been comprehensively documented and studied in the academic literature.

4 Method

We employed qualitative case study research since this methodology allows us to obtain an in-depth understanding of the policy dynamics and the mechanisms driving them over time (Yin, 2009, Eisenhardt and Graebner, 2007).

For our analysis we drew on two main data sources. First, to obtain a broad understanding of the contextual factors we conducted a series of semi-structured interviews with 21 designated PV industry experts.5 Experts were sampled in a way that ensured that they covered different positions in the industry and that they provided both insiders’ and outsiders’ perspectives on the policy making process. Of the experts interviewed, 7 were directly involved in the legal process, e.g., by being members of the German national parliament, working in the ministry of environment or serving as experts for expert committees. Among those interviewees not directly participating in the

4 While we define PV as our unit of analysis, the fact that this technology is embedded in a larger technological system, encompassing for example the electricity grid, makes an isolated consideration of PV impossible. In our analysis, we therefore include developments in and effects on adjacent technologies whenever necessary.

5 Interviews lasted between 60 and 90 minutes and were conducted by at least two researchers to ensure the reliability of the findings.
political process were investors, project developers, representatives of firms producing PV modules and manufacturing equipment, scientists and market analysts.

Second, as the primary source of information, we conducted a comprehensive analysis of more than 700 archival documents describing both the process and outcome of policy making for the German FIT system for PV. We began by collecting the legislative texts pertaining to the German Renewable Energy Sources Act (EEG) with its 8 amendments. These documents served as a data basis to describe how the policy as the **legislative basis** related to the German FIT has changed over time. To obtain an in-depth understanding of the **policy process** that led to the changes in legislation, we then searched the archive of the German National Parliament (‘Bundestag’) for documents containing the keywords ‘solar’, ‘solar energy’, ‘solar power’, ‘sun power’ and ‘photovoltaic’ (in German). This search yielded 715 documents of which 170 were deleted because they were considered of little value for our analysis. Finally, to understand the effects of the policy on the broader socio-technical system, we gathered additional quantitative and qualitative data on annual and cumulative PV deployment, industry development, jobs, annual and cumulative costs as well as PV system prices in Germany. In this context, among other sources, we screened 6 additional expert studies dealing with the German FIT for PV as well as 166 issues of the leading industry magazine “Photon” from 1996 to 2011. An overview of the archival documents we analysed as part of our study is given in Table 1. Moreover, Table A.1 in the appendix contains a list of the 57 most important documents in chronological order.

To derive theoretical insights from our data sources, the interview transcripts and archival documents were analysed using qualitative content analysis. Following the logic of TIS analyses, we first used ATLAS.ti to code the documents describing the policy process to identify prevalent issues, i.e., blocking mechanisms and other drivers mentioned as a rationale for policy implementation in the policy discourse. Using a bottom-up, iterative coding procedure, we identified a total of 2,354 text elements which we grouped into 15 issue categories (see Table A.2 in the appendix for an overview of the categories and their frequency of occurrence in the documents over time). In a second step, we then applied pattern matching to establish relationships between the identified issues, implemented policy measures and the observed changes in the socio-technical system (Yin, 2009). Triangulation of our various data sources allowed us to uncover for each point in time whether and why policy makers were acting upon prevalent issues in the socio-technical system, how the policy interventions taken resulted in changes in the socio-technical system and how these system changes, in turn, affected the issues discussed in the further political discourse.

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6 To understand the origin of the 2000 Renewable Energy Sources Act, the analysis of archival documents comprised archival data reaching back as far as 1980.
Taken together, this analysis provided insights on the relevance of system complexity, i.e., the extent to which developments in the system and consequences of policy interventions were intended or foreseen. By analyzing the rhetoric and action of the political actors in detail we could further control for the role of politics.

### Table 1: Overview of analyzed archival documents

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</tr>
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<td>Protocols of sessions of German Bundestag</td>
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<td>Legislative drafts and petitions</td>
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<td>Protocols and reports of expert committees</td>
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<tr>
<td>Briefings by the German government (incl. EEG experience reports)</td>
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<tr>
<td>Protocols of parliamentary question times (incl. answers)</td>
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<tr>
<td>Minor interpellations directed to the German government (incl. answers)</td>
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<td>Major interpellations directed to the German government (incl. answers)</td>
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</tr>
<tr>
<td>Issues of industry magazine “Photon”</td>
<td>166</td>
</tr>
<tr>
<td>External expert studies</td>
<td>6</td>
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<tr>
<td><strong>Sum</strong></td>
<td><strong>725</strong></td>
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Based on the insights gained through this process, we developed a description of the evolution of the German FIT for PV over time (see Section 5). Abstracting our findings allowed us to derive a theoretical framework describing the dynamics of targeted policy interventions in socio-technical system (Sections 6.1 and 6.2). Finally, by tracking the main issues in the socio-technical system over time, we were able to scrutinize interactions between the function of ‘market formation’ with other functions of the TIS (e.g., ‘legitimation’ and ‘entrepreneurial experimentation’). The findings of this analysis will be taken on in Section 6.3 in order to discuss whether the different functions of a TIS can indeed be assumed to interact in a purely positive manner.
5 Evolution of the German FIT System for PV

In the following, we describe the evolution of the German FIT system for PV from 2000 to the beginning of 2012. For the sake of readability, we cluster the development of the instrument into four phases during each of which policy makers focused on specific changes in policy design. For each of the phases we first describe the main issues in the socio-technical system. We then discuss the implemented policy changes targeting these issues as well as the effects these had on the socio-technical system. During our description, we use the codes D1 to D54 to reference the original policy documents listed in Table A.1 in the appendix. An overview of the four phases, displaying the respective system issues, implemented policy changes and effects on the socio-technical system is given in Table 2. Supporting the information in Table 2, Table A.3 in the appendix shows how the relative importance of issues in each of the phases has evolved over time.

Phase 1: Establishing a Sufficient Financial Incentive (until 2000)

Prior to the year 2000, development and deployment of PV technologies in Germany were not driven by national feed-in tariffs but a mix of direct R&D funding, smaller local initiatives and two large demonstration programs, the 1,000 and the 100,000 roofs program. In the year 1991, based on a report of a cross-party working group (the so-called ‘Enquete Komission’ – see document D1 in Table A.1 in the appendix), the first Feed-in Law (‘Stromeinspeisungsgesetz’- D2) was established by the governing coalition consisting of the Christian Democratic (CDU) and the Liberal Democratic Party (FDP). However, this law “had no measurable effect on the use of photovoltaic power” (D7) since the remuneration at a level of 90% of the average customer purchasing price was much too low to cover costs of PV power producers.

Throughout its reign, the CDU/FDP government opposed any increase in the FIT for PV with the argument that subsidizing the technology was uneconomic and further market interventions should be avoided (D3, D5). Instead it was stressed that due to the early stage of development, support for R&D and demonstration was best suited to advance PV (D10). Politicians of the Social Democratic Party (SPD) and Greens, on the contrary, emphasized the importance of a mass market for lowering the costs of PV (D8). They pointed to the fact that other countries, such as Japan and the US, had already established more comprehensive market support schemes, raising concerns that Germany might lose the international race for PV industry development (D4, D6, D9, D10). Moreover, especially the Green party considered the broader market support of PV a means to break the market power of the large German utilities (D8).
|-------|------------------------------------------|----------------------|-----------------|-------------------------|---------------------------------|
| 1     | • Lack of maturity and high cost of PV technology  
      • Lack of mass market for PV  
      • Insufficient financial incentive for power producers of PV  
      • Market power of large utilities  
      • Market support as chance to build PV industry and create jobs | 2000 | SPD & Green | • Introduction of Renewable Energy Sources Act  
      • Technology-specific but size-independent remuneration of 51 EUR cents/kWh over 20 years  
      • Maximum size of 5MW for building integrated plants, 100kW for others  
      • Fixed degression of 3% p.a.  
      • Ceiling for annual installed capacity at 350 MW  
      • Exclusion of utilities with share of EEG electricity > 50% in overall sales from having to pay EEG apportionment (‘Grünstrom-privileg’) | • First boost in deployment (186 MW installed in 2001)  
      • No. of jobs grows slowly to 4000 in 2001  
      • Rise in annual difference costs from 19 M EUR in 2001 to 37 M EUR in 2003 |
| 2     | • Market support as chance to build PV industry and create jobs  
      • Market support as chance to increase exports  
      • High cost and rising electricity prices (problematic especially for energy-intensive industry) | 2002 | SPD & Green | • Ceiling for annual installed capacity raised to 1000 MW  
      • Reduction of EEG apportionment (0.05 EUR cents/kWh) for large electricity consumers with a consumption > 100 GWh, electricity cost per gross value added > 20%  
      • Removal of ceiling for annual installed cap. and plant size  
      • Increase in remuneration for roof-top PV to 54.7 EUR cents/kWh | • Strong rise in deployment (4.170 MW installed at the end of 2007)  
      • Reduction of PV system price from 6 EUR/Wp in 2002 to 4.3 EUR/Wp in 2008  
      • Strong rise in no. of jobs to 40,400 in 2007  
      • Rise in annual difference costs to 1.47 bn. EUR in 2007 |
| 3     | • High cost for society and rising electricity prices  
      • Excess remuneration and windfall profits for PV industry  
      • Increasing competition from China  
      • Risk of hurting domestic industry | 2009 | CDU & SPD | • Dynamic degression of remuneration depending on deployment (basic degression of 8 to 10% for 2010 ± 1 percentage point if annual installed capacity < 1000 MW or > 1500 MW)  
      • Requirement to install remote control and power measurement unit for plants > 100 kWh  
      • Option of self-consumption (25.61 EUR cents/kWh) or direct marketing to third parties | • Further increase in deployment (24.678 MW installed at the end of 2011)  
      • Slowing market growth  
      • Rise in no. of jobs to 150,000 in 2011  
      • Rise in annual difference costs to 6.8 bn. EUR in 2011  
      • Strong reduction of PV system prices from 4.3 EUR/Wp in 2008 to 2.05 EUR/Wp at the end of 2011 |
| 4     | • Increased power intermittency and power regulation  
      • Risk of reduced grid stability  
      • Lack of market integration  
      • High cost for society and rising electricity prices | 2011 | CDU & FDP | • Adjustment of depression for 2011 by 3%, 6%, 9%, 12% or 15% depending on deployment in March to May 2011  
      • Adjustment of depression for 2012 (9% basic depression, reduction or increase depending on deployment in 2011) | • ? |
|       |                                        | 2012 | CDU & FDP | • Alternative between limiting inverter power to 70% of PV plant capacity or installation of remote control for plants < 30 kW  
      • Remuneration for self-consumption depending on system size (max. 12.36 EUR cents/kWh)  
      • Further extension of reduction in EEG apportionment for large electricity consumers: criteria adjusted to consumption n > 1 GWh, electricity cost per gross value added >14%  
      • Limitation of ‘Grünstromprivileg’ (see Phase 1) to 2 EUR cents/kWh  
      • Introduction of market premium as incentive for direct marketing |
When in 1998 the CDU/FDP government was replaced by a coalition consisting of the SPD and the Green Party, the new government set up a completely new feed-in law, the Renewable Energy Sources Act (‘Erneuerbare Energien Gesetz’ – EEG – D11). The law consisted of 12 articles and was enforced on the 1st of April 2000. Similar to the first Feed-in Law, the EEG granted independent producers of PV access to the electricity grid if a grid connection was “necessary and economically feasible”. Beyond this, however, for the first time the law included a PV-specific remuneration of 51 EUR cents/kWh\(^7\) at which grid operators had to purchase the generated electricity over a guaranteed period of 20 years. The remuneration paid by the grid operator was forwarded to the electricity utility which apportioned the extra costs (so-called ‘EEG apportionment’) to the electricity price of the end consumer. Only utilities whose total sales included more than 50% of FIT-eligible electricity were excluded from having to collect the EEG apportionment, creating an extra incentive for utilities to increase their share of renewables in their electricity portfolio. To account for the expected decreases in the cost of PV resulting from technological learning and economies of scale, the law included an annual degression of 5% in the FIT for newly installed plants as of 2002.\(^8\)

In combination with low-interest loans provided under the 100,000 roofs program, the significant increase in the remuneration for PV led to a surge in the market for PV technologies. Annual installed capacity escalated from only 9 MW in 1999 to more than its 15-fold in 2003 (see Figure 2). The first experience report on the EEG, commissioned for the German Bundestag and published in June 2002, noted that PV showed the smallest contribution to the electricity generation (0.05% in 2001) but the highest growth rates (D12). The EEG was subtly rated a success and it was expected that the additional incentives set by the 100,000 roofs program could be abandoned in 2004.

**Phase 2: Removing Barriers to Market Growth (2000-2004)**

With the EEG providing a sufficient financial incentive for an increased investment in PV, two issues emerged that the 2000 version of the EEG did not take into account. First, to allay concerns among opposition parties and consumer agencies that the EEG would lead to steep increases in electricity prices, the EEG 2000 included a cap of 350 MW for the maximum annual installed capacity to be covered by the feed-in tariff. Simultaneously, the plants eligible for the remuneration were limited to a maximum size of 5 MW for roof-mounted PV and 100 kW\(_p\) for other facilities. In the view of an emerging domestic PV industry, both of these factors were considered potentially

\(^7\) All monetary values in this document are expressed in nominal terms.

\(^8\) It is important to note that the degression mechanism leaves the tariffs of installed plants unchanged, i.e., plant operators are guaranteed the FIT tariff at the time of installation throughout the twenty years, irrespective of later changes in legislation.
harmful barriers to the arising opportunity of establishing a lead market position and exporting domestic PV technology (D12). Second, with increasing deployment the share of the EEG apportionment in the end consumer electricity price rose from 0.2 EUR cents/kWh in 2000 to 0.4 EUR cents/kWh in 2004 which led to concerns about potential competitive disadvantages for energy-intensive sectors (D14, D16).

To address these issues, in 2002 the German Bundestag adopted an addition to the EEG which raised the annual ceiling to 1000 MW (D13). Moreover, in a first amendment of the EEG in July 2003, an article was added that limited EEG apportionment for large electricity consumers with an electricity consumption of more than 100 GWh and a share of electricity costs in gross value added of more than 20% to 0.05 EUR cents/kWh (D15). In a second amendment in December 2003 (D18), the annual ceiling and the limit to eligible plant sizes were completely removed. For roof-mounted PV the remuneration was raised to up to 57.4 EUR cents/kWh which was justified by the fact that with the end of the 100,000 roofs program private households could no longer apply for complementary low-interest loans (D19). All of these changes were mainly promoted by the SPD/Green government coalition. In general, however, the EEG also enjoyed support by many

Figure 2: Cumulative installed PV capacity in Germany
(data from EPIA, 2012, BMU, 2012)
politicians in the CDU who, while pointing to areas of improvement, praised its general effectiveness (D14, D17).

In July 2004 the EEG 2000 with its additions and amendments was substituted by a completely overhauled new EEG, consisting of 21 articles (D20). The revision had officially been stipulated in the EEG of 2000 and reinforced the development reflected in the previous additions. Several articles were added that detailed the processes of remuneration payment and grid connection to ensure a higher investment security of independent power producers. Furthermore, the limitation of the EEG apportionment for large electricity consumers was extended to include all companies that used more than 10 GWh of electricity and had a share of electricity costs in gross value added of more than 15%.

The increase in the remuneration for rooftop PV and the removal of the ceilings for maximum plant size led to a fundamental boom of installations in Germany. The installed capacity rose from 435 MW at the end of 2003 to almost 6 GW at the end of 2008. The 2007 experience report noted that the 2010 target for deployment of PV would already be reached at the end of 2007 (D27). Due to its positive effects on domestic job creation, CO₂-free electricity supply and innovation, the overall assessment of the law was very positive. Especially the growing number of jobs in firms producing and installing PV modules and manufacturing equipment (see Figure 3) led to an unprecedented excitement among politicians of all parties. In many debates, the EEG was praised as a success story (D22, D23, D26, D28, D29, D30). Even the FDP, which as the only party favored market-based instruments, such as tradable green certificates over a FIT, urged measures to support the export of German PV technology (D24, D25).


Prior to 2006 the SPD and the Green Party, as the originators of the EEG, had been able to justify the public costs for PV by pointing to the positive economic, ecological and social side effects of the FIT which were supposed to outweigh the investments in the medium term. Furthermore, politicians of both parties pointed to the large amounts of public spending that had been directed to other energy technologies, e.g., nuclear power, in the past (D17). In contrast to this, some members of parliament of the CDU and FDP voiced criticism regarding the high social costs resulting from the FIT for PV, e.g., in a large interpellation in 2004 (D21). However, all parties generally shared the goal of supporting PV and especially after a government consisting of SPD and CDU had been elected in 2005, critics of the EEG in the CDU maintained a low profile.
With the steep increase in deployment that occurred from 2004 to 2008, the costs that had to be borne by the electricity consumer became increasingly significant and the focal point of the political debate. In 2008, the extra cost for electricity consumers due to PV support through the FIT amounted to almost 2 bn EUR – an increase of more than 600 percent compared to the level of 2004 (see Figure 4). In addition, it showed that production costs for PV modules during the years 2004 to 2008 had decreased at a much faster rate than the remuneration paid through the FIT system (D34). These cost reductions, which were the result of successful innovation efforts of firms and economies of scale, led to considerable windfall profits for technology and power producers (D31, D34).

In response to these challenges, in 2009 a new EEG was enforced which contained specific measures to “dampen the market development”, limit additional costs for consumers and reduce windfall profits (D33). As the most significant change, the static depression of 5% was substituted by a dynamic depression (‘flexible ceiling’) which meant that the level of remuneration paid for new plants was dependent on the installed capacity of PV in the previous year. This new mechanism, which had been suggested by the Green Party to avoid a fixed ceiling, was supported by all parties except the LINKE (D32). As a measure to reduce adverse effects of PV on grid stability and avoid investments in distribution grids, the 2009 amendment of the EEG also introduced targeted incentives for self-consumption of electricity. Furthermore, based on recommendations in the 2007
experience report, the amendment to the EEG in 2009 contained a new article which required plants with a size larger than 100 kW to implement a remote control and power measurement unit. This measure was meant to provide grid operators with the possibility to disconnect larger plants from the grid in case of instability. To make up for the financial losses occurring during such a period of transitional grid enforcement, plant operators were legally guaranteed compensation at the level of lost income. The EEG 2009 also reformed the redistribution mechanism underlying the EEG apportionment. Instead of purchasing the electricity and bundling it into contracts to be sold to electric utilities, grid providers were now required to directly market the electricity bought from PV plant operators at the electricity spot market. Moreover, to slowly integrate the renewables into the market and reduce mismatches between electricity demand and the supply, the EEG 2009 also introduced the option for plant operators to forgo the FIT and directly market their electricity to third parties.

Despite the increased degression of FIT levels, deployment of PV kept rising at strong rates. Due to overcapacities among producers of PV modules, an increasing supply of low-cost modules from Asia (especially China) and a significant drop in prices for the raw material silicon (D38, D39, D40), PV system prices plummeted by 29 percent from 4,225 EUR per kWp at the end of 2008 to 3,000 EUR
per kWp at the end of 2009 (see Figure 5). Since the FIT level declined at a much lower pace, profits of both producers and investors rose. Together with the breakdown of the Spanish PV market, which now could no longer absorb the large quantities of PV modules produced (D38), this led to a record capacity of 3.8 GW being installed in Germany in 2009. The fact that this further raised the annual difference costs to be carried by consumers was deemed particularly undesirable since the share of German manufacturers in global PV cell production had fallen quite significantly since 2007 and more and more modules installed in Germany were supplied by Chinese manufacturers (see Figure 6). As a consequence, a number of media reports appeared that saw the FIT itself as one of the main reasons for the competitive disadvantage of the German PV industry which, in the face of generous support had neglected technological innovation and geographic diversification (D35, D43). Formerly quoted as exemplary, the support for PV was now criticized even by advocates of the German FIT system who worried that the developments within PV could reduce the public acceptance of renewables and undermine the legitimacy of the FIT system as a whole (D37, D47, D48, D49, D51, D52).

In reaction to these developments, the conservative government consisting of CDU and FDP, which had replaced the CDU/SPD government in September 2009, introduced a legislative draft according
to which FIT levels of PV ought to be cut by 20 percent (D36). Although, particularly in the later phases of the legislative process, there was a general consensus among all parties that the level of the FIT for PV had to be reduced, SPD, Greens and LINKE opposed such drastic reductions, pointing out that they would hurt the domestic industry and that windfall profits in the PV industry were negligible compared to the profits made by the large utilities (D35, D41, D42). Finally, in August 2010, an amendment of the EEG was enforced that significantly reduced remuneration for all system sizes retroactively for July 2010 (D46). Degression for 2010 and 2011 was adjusted upward. Furthermore, two one-time reductions were applied which lowered remunerations by 10% and 3% in July and October 2010 respectively. The fact that reductions were much lower than originally envisioned was mainly due to the fact that conservative representatives from eastern states, in which the majority of PV technology producers are located, opposed any one-time reductions in the FIT beyond 10% (D44).

![Figure 6: Global PV cell production and share of PV cells produced in Germany (data from Photon, 2012)](image-url)

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9 The fact that, despite previous opposition by the FDP, the FIT was not abandoned by the conservative-liberal government can be attributed to the fact that solar power enjoyed widespread support in the German population and that with 60,000 jobs the industry had become an important economic factor.
Despite these measures, annual installed capacity in 2010 reached an all-time high of more than 7.4 GW. Therefore, degression rates were further raised in another amendment of the EEG in May 2011 (D53), such that the FIT levels at the beginning of 2012 reached a level of only 40% of those in 2004. Opposition to these cuts in the FIT was limited (D50, D51). Although in 2011 another record capacity of 7.5 GW was installed, the slower growth in additional capacity indicates that the more forceful approaches of policy makers to dampen market growth finally proved effective. However, with annual difference costs amounting to more than 6.8 bn EUR in 2011, costs remained an important topic in the public and political debate preceding the adoption of the EEG 2012.

**Phase 4: Ensuring the Seamless Integration into the Market and the Electricity Grid (since 2011)**

To alleviate potential negative consequences from rising electricity prices, with the EEG 2012 the CDU/FDP government further extended the limitations in the EEG apportionment for energy-intensive companies. Since this implied an additional rise in the EEG apportionment for non-privileged consumers, Greens, SPD and LINKE accused the government of not being interested in lowering the burden for consumers (D56, D57). At the same time, however, with PV deployment strongly rising and prices of PV systems strongly declining, two important questions other than social costs moved higher up on the political agenda: 1) How to integrate the increasing capacity of intermittent power into the electricity grid without compromising its stability and 2) how to structure incentives in a way that allows seamlessly phasing out the FIT scheme once cost competitiveness is reached (D54).

After deployment continued to rise in 2009 and 2010, first experts openly warned of “considerable conflicts” (Rainer Baake, German Environmental Aid, D45) and “massive problems” (Stephan Kohler, German Energy Agency, D54) with grid stability if no measures were taken. Hence, the question of grid integration was taken on more seriously in the political debate and addressed in the EEG 2012 (D57). The new legislation consisting of 88 articles became effective in 2012. Among others, it required new plants of any size to have a remote control, allowing the grid operator to disconnect it from the grid. Furthermore, the fixed remuneration for self-consumption was replaced by a self-consumption bonus paid in addition to substituted retail electricity prices. This measure was expected to foster household investments in energy storage and demand-side management (D54).

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10 Only for plants with a size smaller than 30 kW, could the operator alternatively choose to limit the power of the inverter to 70% of the plant capacity, thereby reducing the intermittency of PV electricity.
To incentivize market integration of PV, the EEG 2012 granted operators a market premium if they forewent the FIT and directly marketed their electricity on the spot market. While in general this step was considered useful by experts, they criticized the decision of the government to simultaneously limit the possibility for utilities to benefit from the ‘Gruenstromprivileg’ (see phase 1), which had previously been the most important scheme for incentivizing direct marketing (D54). Moreover, the direct marketing of PV is complicated by the fact that the change in the redistribution mechanism in the EEG 2009 PV itself had strongly contributed to lowering peak-load electricity prices through the so-called ‘merit order effect’ (D54, D55). Since in 2012 the costs of PV are still comparatively high, only a very small percentage of PV electricity is directly marketed. With LCOE having fallen below retail prices, however, direct marketing of PV is expected to play an increasing role in the future as the political support through the FIT can slowly be phased out (D54).

6 Discussion

In the following, based on our analysis of the evolution of the German FIT system for PV, we discuss how policy interventions targeted at inducing technological change served as both a response to and a source of issues in the socio-technical system. Building upon this, we propose a theoretical model describing how the complex dynamics of socio-technical systems shape the process of policy interventions targeted at inducing technological change. Finally, we draw conclusions from literature on TIS and discuss how our study might contribute to an improved integration of the literature on TIS with the one on reflexive governance.

6.1 The German FIT as an Example of Successful Policy Learning

The description of our findings in Section 5 shows that the German feed-in tariff system for PV went through a large number of legislative changes, each of which addressed specific issues in the socio-technical system. The fact that the overall installed capacity of PV in Germany rose from 76 MW at the end of 2000 to 24,678 MW in 2011 shows that policy makers were very effective in resolving issues and inducing ‘market formation’. In fact one of the key success factors in the design of the German FIT for solar PV lay in its inclusion of formal feedback and adjustment mechanisms.

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11 Interestingly, by lowering prices on the electricity spot market, PV also contributed to raising the official amount of EEG apportionment as the average wholesale prices served as the benchmark for calculating the difference cost attributed to renewables support.
From the start, policy makers were aware that the law had to be revised and implemented a
revision cycle that was supported by expert consultations, frequent political interpellations and
numerous experience reports commissioned from external authorities. This institutionalization of
learning on the side of the policy maker allowed a continuous evolution and adaptation of the
legislation in a highly dynamic socio-technical environment.

6.2 Policy-Induced Technological Change as a Driver of Issues

Therefore, while the German FIT for solar PV can be regarded as a stellar example for successful
policy learning and reflexive governance, our analysis revealed that not only the solution of issues
but also the emergence of new ones was closely related to policy interventions in the socio-technical
system. In fact, while policy incentives successfully resolved prevalent issues, technological change
induced by the FIT scheme often led to the emergence of new, unexpected issues to be targeted in
subsequent steps. In the following we present four examples to illustrate this point.

First, while fostering the deployment of PV was the explicit goal of the policy scheme, in the case of
the German FIT for PV the speed of deployment was continuously higher than what policy makers
had expected. The German Ministry of the Environment, for example, stated on its website that “in
case of the desired, strong growth of renewable energies the burden [for consumers] will amount to
mere 0.1 EUR cents per kWh in a couple of years” (BMU, 2000). Due to the unexpectedly strong
deployment induced by the FIT, the EEG apportionment already exceeded this value within the
first year after the FIT had been introduced and amounted to 3.53 cents per kWh, more than the
35-fold, in 2011. The rise in social costs that went along with the unforeseen, high market growth
induced policy makers to implement a number of changes to the FIT, many of which led to the
emergence of new issues. For example, there is evidence that rather than reducing deployment,
publicly contemplated cuts to the FIT level further spurred investments in the short-term since
investors in PV plants feared that investments might become unprofitable in the future (D50, D51).
Furthermore, the exemptions implemented to limit the rise in electricity prices for energy-intensive
industry further raised the costs to be borne by the average electricity consumer (D55, D56).

Second, from the beginning the German FIT for PV was designed to foster technological innovation
and lower the cost of the technology, e.g., by enabling mass production. For this purpose, the first
EEG already included a 5% degression, which as a policy maker we interviewed reported, had been
chosen based on “usual learning rates of comparable industries”. However, “technology costs fell
much faster than [had] been expected” which was due to “economies of scale and research activities
by private corporations which have been sparked by the EEG” (Katharina Reiche, Parliamentary
Undersecretary of State, D34). While of course this development can be considered a positive achievement, it required subsequent changes to the policy to avoid windfall profits for investors and producers of PV technology.

Third, the unexpected speed of policy-induced deployment can also be seen as the main driver of the more recent issues of grid and market integration (phase 4). Already in the 1980s, well before FITs were put in place, it was known that deploying large amounts of PV as an intermittent energy source would put stress on the electricity grid (D1). Yet, the fact that the first versions of the EEG up to 2009 did not contain any measures addressing this issue indicate that policy makers did not expect integration of PV capacity to become a problem in the near future. With installed capacity of PV continuously growing at an unpredicted pace, first measures were finally implemented in the EEG 2009 that are directly targeted at enhancing grid stability, such as remote control or the limitation of inverter power. Moreover, in 2012 a program was put in place that requires operators of PV plants to retrofit existing systems to avoid fluctuations in the power frequency (the so-called ‘50.2 Hertz problem’), clearly showing that the issue of grid integration had previously been undervalued by regulators.

Finally, the rise of a Chinese PV industry, which increasingly sold its products to the German market also came largely as a surprise to German policy makers. Until 2007, German manufacturers were considered “world market leaders” (D24) and politicians of all parties were enthusiastic about the creation of jobs in an emerging industry which had been an important in developing the FIT. However as of 2007, the attractive incentives provided by the EEG increasingly attracted foreign companies that were able to generate revenues and “invest these resources in research in development” (Dr. Holger Krawinkel, D41). In this sense, as a policy maker we interviewed admitted, the German EEG itself “played a decisive role in the emergence of the Chinese PV industry”. With import ratios increasing over time, the EEG suddenly benefited foreign producers to a higher degree than the domestic industry. This became an important topic in the political discussion on the appropriate level and design of the support scheme.

Overall, the above-mentioned points indicate a limited ability of policy making to accurately foresee consequences of targeted interventions in TIS. While some were partly foreseen, many issues resulting from policy interventions targeted at inducing technological change came as a surprise or were underestimated with regard to timing or scale. As one of the experts we interviewed reported, it is hard for policy makers to proactively address issues since “every change in a detail [of the regulation] can develop a dynamic which you did not intend”. In line with this, one policy maker we interviewed expressed that “with the EEG we are getting to the limits of what policy can do. It is difficult to foresee the development”. When developing schemes for market support, policy makers
therefore “have to react to the tempestuous technological developments in the market. Over and over, we will have to react.” (Dr. Norbert Röttgen, former German Minister for the Environment, D43). While in many other countries the challenge of reacting to unexpected issues might have induced policy makers to cancel (or not even start) the support scheme, in Germany the high public support for renewables and PV and the existence of a domestic industry with related jobs prevented such a development.

6.3 Framework ‘Compulsive Policy-Making’

In order to translate our findings into a more abstract representation we propose the theoretical framework depicted in Figure 7, that directly addresses our research question of how the complex dynamics of socio-technical systems shape the process of policy interventions targeted at inducing technological change. We suggest that at each point in time, political discussions revolve around a number of issues in the socio-technical system (1). When designing policy incentives (2), policy makers directly address these issues and also try to foresee future ones. In general, however, changes in policies are only directed to a small subset of particularly prevalent issues and rarely present accurate answers to less immediate, future issues. This can be explained by the fact that, in general, the evolution of socio-technical systems is hard to foresee (a). More importantly, however, policy interventions themselves often lead to technological change (3) that resolved the immediate bottleneck but, through complex system interdependencies (e), lead to the emergence of new issues (1). These issues in turn, are addressed by policy makers by changing the focus in policy design and adjusting existing policies (2). The time it takes for issues to be resolved can be expected to vary considerably depending on the detailed nature of the issue. As a result, changes in policy design are usually directed to a number of novel issues while simultaneously addressing older, persisting ones.

While the majority of issues we found in the history of the German FIT for PV can be considered at least partly self-inflicted, there were also developments within the socio-technical system that were beyond the direct control of German policy-makers, e.g., the collapse of the Spanish market in 2009 that raised installations in Germany (d). Furthermore, throughout the evolution of the German FIT system for PV changes in policy design were impacted by issue framing (f) and politics (b). In the first two phases many issues were of a nature that required policy makers to address them if and only if policy makers wished to further a diffusion of PV. As a consequence, in the early phases of the German FIT system for PV, developments were very much driven by political interests and opportunities, such as reducing the market power of large utilities and supporting a domestic PV industry. In the further evolution of the German FIT system for PV, however, unforeseen issues emerged that exerted direct pressure on policy makers to change the policy design.
Political debates became more technical with policy makers increasingly reacting to rather than proactively shaping technological change. Despite remaining considerable discrepancies between the political parties regarding the appropriate means, a broader consensus can be observed that particular issues (e.g., rising social costs or looming grid instabilities) needed to be tackled.

![Figure 7: Framework ‘Compulsive Policy-Making’](image)

We argue that the cycle of issues and solutions we describe in Figure 4 shows strong similarities with what Rosenberg (1969) labeled ‘compulsive sequences’. Studying the evolution of technical systems in the machine tool industry, Rosenberg finds that at any given time firms in the industry focused their search processes on a small number of clearly identifiable problems which constitute the bottleneck of the technical system. Eventually, this search then led to a change in the system which resolved the bottleneck. However due to interdependencies between the system elements, the resolution of the bottleneck caused new bottlenecks in the system to emerge. Since these needed to be resolved to further increase the performance of the technical system, the firm’s direction of...
technical search shifted to the new bottleneck, leading to a continuous cycle of problems and solutions that shapes the evolution of technical systems.12

While obviously there are a number of important differences between a firm trying to improve a technology and policy makers intervening in a socio-technical system (e.g., in terms of the number of actors involved and the decision making process), we maintain that the general pattern is surprisingly similar. Building upon Rosenberg’s terminology, we therefore label the process shown in Figure 4 ‘compulsive policy-making’. It is important to note that in this context, ‘compulsive’ does not imply a lack of agency of policy makers in the political process. Rather, it describes the general phenomenon that interventions in socio-technical systems targeted at inducing technological change alter the configuration of the system, thereby causing changes in the prevalent issues and exerting a pressure on policy makers to change the focus in policy design. It is this explicit link between policy interventions and complex technology dynamics that distinguishes our framework from the ‘science of muddling through’. In Lindblom’s framework (1959) iterations in the policy making process are predominantly due to bounded rationality of policy makers who engage in a process of trial and error to achieve a particular policy objective. The concept of ‘compulsive policy-making’, in comparison, stresses that, even if policy makers are able to achieve a particular objective, technological change induced by policy interventions will often lead to the emergence of new issues in other parts of the system that need to be tackled in subsequent steps.

6.4 Implications for the Literature on TIS

Our findings have important implications for the existing literature on TIS. In general, our results imply that much value can be gained from a systematic analysis of the blocking mechanisms of socio-technical system as is offered by the functional perspective within the TIS framework. Such an analysis can help to understand system dynamics and draw attention to critical issues to be addressed by policy makers.

Yet, at the same time, our empirical analysis highlights the non-trivial nature of interactions between system functions which decisively shape the process of policy interventions in TIS. Our findings suggest that, in contrary to the prevailing view in the literature, interdependencies between

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12 Rosenberg’s concept of ‘compulsive sequences’ was later taken on by Hughes’ (1983) in his work on large technical systems. Similar to Rosenberg, Hughes suggests that complex systems evolve in an uneven manner since at each point in time there are particular system components – so-called ‘reverse salients’ – that lag behind other system components (e.g., in terms of efficiency). Since these reverse salients are interconnected with the other system components, their presence retards the overall performance of the technical system. Therefore, Hughes suggests that at each point in time innovative activity will concentrate on ‘correcting’ the reverse salient.
the functions or key processes of TIS need not necessarily be positive. In the case of the German FIT for PV, supporting ‘market formation’ resulted in considerable social costs to be borne by electricity consumers and – by fostering ‘knowledge development’ – led to windfall profits to the producers of PV modules. While previously the image of PV in the public had been extremely positive, the high costs led to serious criticism of the FIT system for PV and even “threaten the public acceptance of the entire FIT system” (Expert Advisory Board on Environmental Issues, D49 – see also Huenteler et al., 2012). In this sense, in the case of the German FIT for PV, supporting the function of ‘market formation’ negatively affected the function of ‘legitimation’ and, at least to some extent, seems to have had an adverse effect on “entrepreneurial experimentation” among German producers of PV modules (Hoppmann et al., 2013). Moreover, the fact that the German FIT for PV fostered ‘knowledge development’ among and ‘knowledge diffusion’ to Chinese manufacturers of PV modules has clearly had a negative effect on the ‘legitimation’ of the technology in Germany.

Supporting particular functions by successfully removing blocking mechanisms may thus come with undesired, unforeseen effects. We suggest that scholars deriving policy recommendations from TIS analyses try to identify such adverse effects and derive mitigation strategies to cope with these. To enhance the visibility of potential future issues, it seems advisable to combine retrospective TIS analyses with foresight and scenario techniques (e.g., Markard et al., 2009). However, as our analysis shows, the complex dynamics of socio-technical systems render foresight very difficult. Therefore, policy measures should be designed in a high flexible and adaptive way and combined with a frequent monitoring of policy effects (Voß and Kemp, 2006).

6.5 TIS and Reflexive Governance: Towards an Integrated Framework

By stressing the role of policy learning and adaptation in the context of TIS, our framework represents a first step towards a closer integration of the literature on TIS with the work on reflexive governance (Voß and Kemp, 2006). Traditionally, these two important streams within the literature on sustainability transitions have been rather separate. Our empirical analysis of the German FIT system for PV suggests that this current divide is unfortunate as the approaches hold a lot of potential for informing each other. The TIS approach represents a powerful heuristic for identifying system failures (or issues) but tends to underestimate the effect of politics, complex system interdependencies and limited foresight. In contrast, the literature on reflexive governance puts strong emphasis on the inherently political, unpredictable and emergent nature of policy making. As the rather effective German FIT for solar PV shows, however, this potentially undervalues policy makers’ capacity to purposefully alter socio-technical systems. To reconcile these
two perspectives, it seems that we require a better understanding of the detailed mechanisms which shape the dynamics of policy making in complex environments. Our framework builds upon the idea of blocking mechanisms as the focusing devices of policy change, thereby highlighting the value of systemic, analytical approaches to policy-making such as TIS, while simultaneously emphasizing technology dynamics and uncertainty as key mechanisms that limit targeted policy interventions.

7 Limitations and Future Research

Our study has several limitations that lend themselves as avenues for future research. First, one could argue that the case of the German FIT system for PV is special in that with the development of the FIT policy makers in Germany in many ways treaded unchartered trails. The lack of experience with this instrument might have caused problems and iterations, leading to a strong prevalence of ‘compulsive policy-making’. However, there is some indication that in fact countries that implemented FIT schemes at a later point in time – notably Spain, the Czech Republic and Italy – went through similar cycles of policy evolution and sometimes drastically altered policy design in response to the emergence of unexpected issues (del Río González, 2008). To better understand the external validity of the framework proposed in this paper, it would be interesting to juxtapose the evolution of FIT systems in different countries and analyze commonalities in their development.

Second, it seems likely that the degree to which policy makers can foresee developments and successfully intervene in a socio-technical system depends on the complexity of the system. Given the strongly international nature of the PV industry and the high dynamic at which it has evolved over the last years, compulsive sequences might be more pronounced for the TIS of PV than for simpler, geographically bounded systems. Moreover, the observations of compulsive sequences may be specific to interventions in early-stage TIS which experience unstable industry structures, fast technological learning and high rates of growth. Future research seems necessary to examine the existence of compulsive policy-making in TIS for technologies other than PV.

Third, future studies should investigate to which extent the findings of our analysis for FITs can be generalized to other policy instruments and policy mixes. During our analysis we found that the German FIT system has been complemented by a number of policy measures, such as demonstration programs, industry policy measures, export initiatives and grid infrastructure incentives. These additional measures very closely followed the prevalent issues in the socio-
technical system and – like the FIT – drove their occurrence, which provides some first evidence that our framework might be applicable to other forms of policy interventions and policy mixes.

8 Conclusion

With this paper, we contribute to a better understanding of the dynamics that ensue when policy makers engage as system builders to induce technological change. The literature on technological innovation systems (TIS) identifies a number of key processes or functions policy makers should support to foster the development and diffusion of environmentally benign technologies. Currently, however, it remains unclear how complex system interdependencies limit policy-makers’ ability to purposefully intervene in socio-technical systems. To investigate this question, we studied the evolution of the highly effective and widely copied German feed-in tariff system for solar photovoltaics as a policy instrument targeted at ‘market formation’. We find that at each point in time, policy makers in Germany directed their attention to a limited number of issues that were considered particularly important for an efficient deployment of solar photovoltaic technologies. Policy interventions often successfully resolved emerging issues, making the German FIT for PV a good example for successful policy learning. At the same time, however, each policy intervention also changed the socio-technical system in a way that brought new issues to the fore. The newly emerged issues subsequently became the target of subsequent policy efforts, leading to a continuous cycle of policy makers inducing and reacting to technological change. In analogy to what Rosenberg (1969) called ‘compulsive sequences’ we label these cycles ‘compulsive policy-making’. Our findings have important implications for the literature on TIS. Since functions of TIS do not necessarily interact in a positive way, scholars should pay close attention to possible adverse effects when deriving policy recommendations based on TIS analyses. Furthermore, our analysis suggests that, due to the complex interdependencies between the structural elements and functions of TIS and the uncertainties surrounding technological change, outcomes of policy interventions are often hard to predict. As a result, our findings emphasize the importance of policy learning in the context of technological innovation systems and represent a first step towards a closer connection of the literature on TIS with the work on reflexive governance.
References


## Appendix

Table A.1: List of most important documents

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<td>07/12/1990</td>
<td>Legislation on the feed-in of electricity from renewable energies into the public grid (Feed-in law)</td>
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<td>D3</td>
<td>17/03/1994</td>
<td>Response by the German government to the major interpellation by the Green Party: Success record of the German government with regard to climate protection</td>
<td>Antwort der Bundesregierung auf die Große Anfrage der Gruppe BÜNDNIS 90/DIE GRÜNEN: Klimaschutz-Erfolgsbilanz der Bundesregierung</td>
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<td>D4</td>
<td>05/04/1994</td>
<td>Response by the German government to the minor interpellation by the SPD: Future of the solar industry in the Federal Republic of Germany</td>
<td>Antwort der Bundesregierung auf die Kleine Anfrage der Fraktion der SPD: Zukunft der Solarwirtschaft in der Bundesrepublik Deutschland</td>
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<td>D5</td>
<td>27/07/1995</td>
<td>Response by the German government to the minor interpellation by the Green Party: Future prospects of the photovoltaic industry in Germany</td>
<td>Antwort der Bundesregierung auf die Kleine Anfrage der Fraktion BÜNDNIS 90/DIE GRÜNEN: Zukunftsperspektiven für die Photovoltaikindustrie in Deutschland</td>
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<td>D6</td>
<td>13/10/1995</td>
<td>Legislative draft by the Green Party: Draft of a legislation for the revision of the legislation on the feed-in of electricity from renewable energies into the public grid (Feed-in law)</td>
<td>Gesetzentwurf der Fraktion BÜNDNIS 90/DIE GRÜNEN: Entwurf eines Gesetzes zur Änderung des Gesetzes über die Einspeisung von Strom aus erneuerbaren Energien in das öffentliche Netz (Stromeinspeisungsgesetz)</td>
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<td>D7</td>
<td>18/10/1995</td>
<td>Briefing by the German government: Experience report by the German Ministry of Economy on the Feed-in Law</td>
<td>Unterrichtung durch die Bundesregierung: Erfahrungsbericht des Bundesministeriums für Wirtschaft zum Stromeinspeisungsgesetz</td>
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<td>D8</td>
<td>26/04/1996</td>
<td>Legislative petition by the Green Party: 10-point plan for entering the solar age</td>
<td>Antrag der Fraktion Bündnis 90/DIE GRÜNEN: 10-Punkte-Programm für den Einstieg ins Solarzeitalter</td>
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<td>04/12/1996</td>
<td>Response by the German government to the major interpellation by the Green Party: Support of the photovoltaic industry by the German government</td>
<td>Antwort der Bundesregierung auf die Große Anfrage der Fraktion BÜNDNIS 90/DIE GRÜNEN: Unterstützung der Photovoltaik durch die Bundesregierung</td>
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<td>D12</td>
<td>16/07/2002</td>
<td>Briefings by the German government: Report on the state of market introduction and cost development of plants for the generation of electricity from renewable energies (experience report on the EEG)</td>
<td>Unterrichtung durch die Bundesregierung: Bericht über den Stand der Markteinführung und der Kostenentwicklung von Anlagen zur Erzeugung von Strom aus erneuerbaren Energien (Erfahrungsbericht zum EEG)</td>
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<td>D13</td>
<td>23/07/2002</td>
<td>Legislation on the revision of the Mineral Oil Tax Act and other laws</td>
<td>Gesetz zur Änderung des Mineralölsteuergesetzes und anderer Gesetze</td>
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<td>10/12/2003</td>
<td>Response by the German government to the major interpellation by the CDU/CSU: Forward-looking and efficient design of the amendment of the Renewable Energy Sources Act</td>
<td>Antwort der Bundesregierung auf die Große Anfrage der Fraktion der CDU/CSU: Zukunftsorientierte und effiziente Gestaltung der Novelle des Erneuerbare-Energien-Gesetzes</td>
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<td>D18</td>
<td>22/12/2003</td>
<td>Second legislation for the amendment of the Renewable Energy Sources Act</td>
<td>Zweites Gesetz zur Änderung des Erneuerbare-Energien-Gesetzes</td>
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<td>D19</td>
<td>12/01/2004</td>
<td>Legislative drafts by the SPD and the Green Party: Draft for a legislation on the revision of the law pertaining to renewable energies in the electricity sector</td>
<td>Gesetzentwurf der Fraktionen SPD und BÜNDNIS 90/DIE GRÜNEN: Entwurf eines Gesetzes zur Neuregelung des Rechts der Erneuerbaren-Energien im Strombereich</td>
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<td>D20</td>
<td>21/04/2004</td>
<td>Legislation on the revision of the law pertaining to renewable energies in the electricity sector</td>
<td>Gesetz zur Neuregelung des Rechts der Erneuerbaren Energien im Strombereich</td>
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<td>D21</td>
<td>19/10/2004</td>
<td>Major interpellation by the CDU/FDP: Renewable Energies in Germany</td>
<td>Große Anfrage der Fraktion der CDU/CSU: Erneuerbare Energien in Deutschland</td>
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<td>D24</td>
<td>09/11/2006</td>
<td>Legislative petition by the FDP: Solar Entrepreneurship in Germany - Accepting the challenges, taking the opportunity</td>
<td>Antrag der Fraktion der FDP: Solares Unternehmertum in Deutschland – Herausforderungen annehmen, Chancen nutzen</td>
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<td>D28</td>
<td>14/02/2008</td>
<td>Protocol of the German Bundestag, 142nd session, 16th legislative period</td>
<td>Deutscher Bundestag: Stenografischer Bericht 142. Sitzung, 16. Wahlperiode</td>
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<td>D29</td>
<td>18/02/2008</td>
<td>Legislative draft by the German government: Draft of a legislation for the revision of the law pertaining to renewable energies in the electricity sectors and changes of corresponding regulations</td>
<td>Gesetzentwurf der Bundesregierung: Entwurf eines Gesetzes zur Neuregelung des Rechts der Erneuerbaren Energien im Strombereich und zur Änderung damit zusammenhängender Vorschriften</td>
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<td>D30</td>
<td>21/02/2008</td>
<td>Protocol of the German Bundestag, 142rd session, 16th legislative period</td>
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<td>D32</td>
<td>04/06/2008</td>
<td>Proposed resolution and report of the committee for the Environment, Nature Conservation and Nuclear Safety on the legislative draft by the German government on a legislation for the revision of the law pertaining to renewable energies in the electricity sectors and changes of corresponding regulations</td>
<td>Beschlussvorschlag und Bericht des Ausschusses für Umwelt, Naturschutz und Reaktorsicherheit zu dem Gesetzentwurf der Bundesregierung, Entwurf eines Gesetzes zur Neuregelung des Rechts der Erneuerbaren Energien im Strombereich und zur Änderung damit zusammenhängender Vorschriften</td>
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<td>Protocol of written questions including answers by the government received from 27th October to 13th November 2009</td>
<td>Schriftliche Fragen mit den in der Zeit vom 27. Oktober bis 13. November 2009 eingegangenen Antworten der Bundesregierung</td>
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<td>D36</td>
<td>23/03/2010</td>
<td>Legislative drafts by the CDU/CSU and FDP: Draft of a legislation for the revision of the Renewable Energy Sources Act</td>
<td>Gesetzentwurf der Fraktionen der CDU/CSU und FDP: Gesetzes zur Änderung des Erneuerbare-Energien-Gesetzes</td>
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<td>D38</td>
<td>19/04/2010</td>
<td>Reponses by the technical expert Philipp Welter on the list of questions handed in by the parliamentary groups as part of the public hearing of the German parliament – committee for the Environment, Nature Conservation and Nuclear Safety – on the legislative draft by the CDU/CSU and FDP for the revision of the Renewable Energy Sources Act</td>
<td>Antworten vom Sachverständigen Philipp Welter auf die Fragen des Fragenkatalogs der Fraktionen im Rahmen der Öffentlichen Anhörung des Deutschen Bundestages - Ausschuss für Umwelt, Naturschutz und Reaktorsicherheit zum Gesetzentwurf der Fraktionen der CDU/CSU und FDP zur Änderung des Erneuerbare-Energien-Gesetz</td>
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<td>Reponses by the technical expert Dr. Wolfgang Seeliger on the list of questions handed in by the parliamentary groups as part of the public hearing of the German parliament – committee for the Environment, Nature Conservation and Nuclear Safety – on the legislative draft by the CDU/CSU and FDP for the revision of the Renewable Energy Sources Act</td>
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<td>Comments by the technical expert Prof. Eicke R. Weber on the public hearing on the legislative draft by the CDU/CSU and FDP for the revision of the Renewable Energy Sources Act</td>
<td>Stellungnahme von Prof. Eicke R. Weber zur Öffentliche Anhörung zum Gesetzentwurf der Fraktionen der CDU/CSU und FDP eines Gesetzes zur Änderung des Erneuerbare-Energien-Gesetzes des Ausschuss für Umwelt, Naturschutz und Reaktorsicherheit des deutschen Bundestag</td>
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<td>Entschließungsantrag der Fraktion BÜNDNIS 90/DIE GRÜNEN zu der dritten Beratung des Gesetzentwurfs der Fraktionen der CDU/CSU und FDP: Entwurf eines Gesetzes zur Änderung des Erneuerbare-Energien-Gesetzes</td>
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<td>08/06/2010</td>
<td>Briefing by the German government: Law for the revision of the Renewable Energy Sources Act, call for the conciliation committee</td>
<td>Unterrichtung durch den Bundesrat ... Gesetz zur Änderung des Erneuerbare-Energien-Gesetzes, Anrufung des Vermittlungsausschusses</td>
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<td>18/02/2011</td>
<td>Briefing by the German government: Report by the Expert Advisory Board on Environmental Issues: Pathways to 100% electricity generation from renewable energy</td>
<td>Unterrichtung durch die Bundesregierung: Sondergutachten des Sachverständigenrates für Umweltfragen: Wege zur 100 % erneuerbaren Stromversorgung</td>
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<td>23/03/2011</td>
<td>Legislative petition of the SPD: On the way towards a sustainable, efficient, affordable and secure energy system</td>
<td>Antrag der Fraktion der SPD: Auf dem Weg zu einem nachhaltigen, effizienten, bezahlbaren und sicheren Energiesystem</td>
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<td>D53</td>
<td>01/05/2011</td>
<td>Legislation for the implementation of directive 2009/38/EG on the support of the use of energy from renewable sources (EAG EE)</td>
<td>Gesetz zur Umsetzung der Richtlinie 2009/28/EG zur Förderung der Nutzung von Energie aus erneuerbaren Energien (Europarechtsanpassungsgesetz Erneuerbare Energien – EAG EE)</td>
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<td>Proposed resolution and report by the committee for the Environment, Nature Conservation and Nuclear Safety on the legislative draft by the German government for the revision of the law to support the electricity generation from renewable energies</td>
<td>Beschlussempfehlung und Bericht des Ausschusses für Umwelt, Naturschutz und Reaktorsicherheit zu dem Gesetzentwurf der Bundesregierung zur Neuregelung des Rechtsrahmens für die Förderung der Stromerzeugung aus erneuerbaren Energien</td>
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<td>01/01/2012</td>
<td>Law for the preferential Feed-in of Renewable Energies (Renewable Energy Sources Act – EEG)</td>
<td>Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz – EEG)</td>
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Table A.2: Prevalence of issues over time*

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<td>10</td>
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<td>Risk of hurting domestic PV industry</td>
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<td>Risk of reduced grid stability</td>
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*Note that the length and nature of the identified text elements varies. The count of elements is therefore intended to reveal general trends in issue prevalence rather than their exact importance in a particular year.
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<tr>
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<td>0%</td>
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<tr>
<td>Market power of large utilities</td>
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<tr>
<td>Market support as chance to build PV industry and create jobs</td>
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<td>17%</td>
<td>3%</td>
</tr>
<tr>
<td>Market support as chance to increase exports</td>
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<td>7%</td>
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<td>3%</td>
<td>18%</td>
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<td>16%</td>
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<td>Increasing competition from China</td>
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<td>Excess remuneration and windfall profits for PV industry</td>
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</tr>
<tr>
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<td>0%</td>
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<tr>
<td>Risk of hurting domestic PV industry</td>
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<td>Risk of reduced grid stability</td>
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Paper IV
The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems – A Review and a Scenario-Based Optimization Model

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Abstract

Battery storage is generally considered an effective means for reducing the intermittency of electricity generated by solar photovoltaic (PV) systems. However, currently it remains unclear when and under which conditions battery storage can be profitably operated in residential PV systems without policy support. Based on a review of previous studies that have examined the economics of integrated PV-battery systems, in this paper we devise a techno-economic model that investigates the economic viability of battery storage for residential PV in Germany under eight different electricity price scenarios from 2011 to 2020. In contrast to previous forward-looking studies, we assume that no premium is paid for solar photovoltaic power and/or self-consumed electricity. Additionally, we test a large number of different PV and storage capacities to determine the economically optimal configuration in terms of system size. We find that already in 2011 investments in storage solutions were economically viable for very small PV systems under scenarios that assume stronger increases in future electricity retail prices. Given the assumptions of our model, the optimal size of both residential PV systems and battery storage rises significantly in the future. Lower electricity wholesale prices or limited access to the electricity wholesale market further add to the profitability of storage. We conclude that additional policy incentives to foster investments in battery storage for residential PV in Germany will only be necessary in the short run. At the same time, the impending profitability of integrated PV-storage systems is likely to further spur the ongoing trend towards distributed electricity generation with major implications for the electricity sector.

Keywords: Residential Solar Photovoltaic, Battery Storage, Distributed Electricity Generation, Techno-Economic Model, Scenario, Electricity Price
1 Introduction

Renewable energy technologies are expected to play a major role in mitigating pressing societal challenges such as climate change and resource depletion, while contributing to domestic energy security. Among the many options available, solar photovoltaic (PV) power has been found to have a particularly large physical potential for electricity generation (Nitsch, 2007). However, three important barriers to a more widespread use of solar PV are that electricity generation from this source is limited to daytimes, depends on local weather conditions and fluctuates strongly over the year (Joshi et al., 2009). As a consequence, there are often considerable gaps between electricity consumption and the electricity supply of PV plants. With an increasing deployment of PV, such demand-supply mismatches pose an increasing threat to the stability of the electricity system (Eltawil and Zhao, 2010).

An effective means for reducing (and eventually eliminating) the mismatches between electricity demand and electricity supply by intermittent energy sources are storage technologies. Responding to the need for steadier electricity supply, several companies in the PV industry have started to develop and sell storage solutions based on battery technologies (Krause, 2011). Yet, while the possibility of shifting the supply of electricity to different times enhances the value of the electricity produced, adding storage technologies to a PV system also raises the overall investment cost to be borne by plant operators. First countries, like Germany, have therefore announced programs that subsidize the use of storage technologies for residential PV (Photon, 2013). Considering the falling costs for both PV and battery technologies, however, it remains controversially discussed whether and for how long these subsidies are necessary to drive the deployment of storage technologies.

Currently, the academic literature provides little guidance as to when the advantages of combining PV systems with storage can be expected to justify the extra expenses. Existing studies on integrated PV-storage systems mostly focus on the additional costs rather than the added economic value from storage (see Section 2). The few studies that investigate profitability of storage for PV typically examine its potential to raise the share of electricity generated by the residential PV system that is consumed by the household (so-called self-consumption). By investing in storage technologies households can leverage the existing spread between wholesale and retail electricity prices by reducing both the volume of electricity that is bought at retail prices and the one to be sold at wholesale prices (Bost et al., 2011, Braun et al., 2009, Colmenar-Santos et al., 2012). Yet, while these studies have strongly advanced our knowledge about the role that storage can play for residential PV systems, two main shortcomings remain. First, existing studies examine the economic viability of storage under the assumption of policy support in the form of feed-in tariffs for solar photovoltaic power and/or additional premiums for self-consumed electricity. However, feed-in
tariffs in many countries have significantly decreased over the last years and are expected to be phased out in the foreseeable future (Hoppmann et al., 2012). Therefore, it seems important to investigate the profitability of storage in an environment without demand-side subsidies for PV and storage technologies. In this case wholesale and retail electricity market price developments will strongly affect storage profitability. Second, and more importantly, existing forward-looking studies that investigate the profitability of storage for residential PV have usually investigated a limited number of sizes for both the PV system and the battery storage. However, especially under the assumption of no additional policy incentives, the chosen size of the PV system and battery storage strongly affect the economic viability of the integrated PV-battery system. This is because the self-consumption ratio is highly sensitive to these parameters. As a result, it currently remains unclear when storage investments will be economically viable for a household that strategically optimizes the size of the PV system and the battery storage at the time of investment.

With this paper, we address the two previously mentioned shortcomings by investigating the question when and under which conditions battery storage will be economically viable in residential PV systems without demand-side subsidies for an economically optimized system configuration. Building upon a review of existing studies that have examined the economics of integrated PV-storage solutions, we present the outcomes of a techno-economic model that calculates the profitability of storage for distributed PV from 2011 to 2020. To account for uncertainties in the future development of technology costs and electricity prices, we draw on 8 electricity price scenarios and conduct a comprehensive sensitivity analysis. Analyzing the optimal PV system size, the optimal storage size and the profitability of storage under each of these scenarios allows deriving important implications for policy making and the trend towards distributed electricity generation.

The remainder of this paper is structured as follows: Section 2 reviews existing studies that have investigated PV systems with storage solutions and discusses existing shortcomings. Section 3 explains the data and method underlying our techno-economic model, followed by a discussion of the model results in Section 4 and their implications in Section 5. The paper concludes with a description of the study’s limitations, suggestions for future research (Section 6) and a brief summary of the main results (Section 7).
2 Literature Review

An overview of past studies that have investigated the economics of battery storage in distributed PV systems is given in Table 1. It shows that in recent years a number of articles have been published that examine how different input parameters, such as PV system and storage size, affect specific economic output parameters, e.g., the cost of electricity or the profitability of the integrated PV-battery-system.

Some authors do not specify the PV technology they model. Those that do usually opt for crystalline silicon PV (for an overview of PV technologies and their respective merits and shortcomings see Parida et al., 2011, Peters et al., 2011, Kazmerski, 1997). Similarly, among the different options available for battery storage (see Hadjipaschalis et al., 2009, Divya and Østergaard, 2009 for an overview), all authors except Bost et al. (2011) and Braun et al. (2009) focus on lead-acid batteries as the currently least expensive alternative for use in residential PV (Sauer et al., 2011).

To economically assess the inclusion of storage in distributed PV systems, the majority of studies calculate the cost of electricity that results when installing storage of a particular size. In these studies, storage is often used as a means to reach a predefined level of energy autonomy or self-consumption (e.g., in off-grid applications), such that the chosen system configuration is generally not compared to a configuration without storage. So far, only few studies, namely Bost et al. (2011), Braun et al. (2009), Clastres et al. (2010) and Colmenar-Santos et al. (2012), explicitly compute economic revenues from storage investments. Clastres et al. (2010) investigate the possibility of a household providing ancillary services and find that, even considering forecasting errors of electricity production, a household could profitably supply active power. In contrast, similar to the focus of this study, Bost et al. (2011), Braun et al. (2009) and Colmenar-Santos et al. (2012) see the main financial incentive for investments in storage in leveraging the gap between retail and wholesale prices. They assume that, by using storage, a household may raise the self-consumption ratio, i.e., the share of PV electricity that is consumed by the household. Since this reduces both the amount of electricity to be fed into the grid at wholesale prices and the electricity to be purchased at retail prices, investing in storage may increase the household’s return from the PV plant. Neither Bost et al. (2011), nor Braun et al. (2009), nor Colmenar-Santos et al. (2012), however, find investments in storage to be profitable at the time of investigation. Therefore, Bost

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1 The list of publications is limited to original papers dealing with small PV systems (< 15kW) and does not include studies of integrated PV-storage systems in hybrid applications (e.g., in combination with wind power or diesel generators).

2 Note that Bost et al. (2011), following the logic of the ‘grid parity’ concept, evaluate the profitability by comparing levelized cost of electricity with a mix of retail and wholesale price that depends on the self-consumption ratio of the household. Braun et al. (2012) and Colmenar-Santos et al. (2012), in contrast, use the metric of internal rate of return.
et al. (2011) and Braun et al. (2009) additionally test profitability for future points of investment, assuming declining investment costs for both the PV system and the battery storage over time.

Table 1: Overview of studies investigating the economics of battery storage in distributed PV systems

<table>
<thead>
<tr>
<th>Author</th>
<th>PV Technology</th>
<th>Battery Technology</th>
<th>Varied Input Parameters</th>
<th>Econ. Output Parameter</th>
<th>FIT*/ SC** premium?</th>
<th>Time of investment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arum et al. (2009)</td>
<td>Not specified</td>
<td>Not specified</td>
<td>PV system and storage size</td>
<td>Cost of electricity</td>
<td>No/No</td>
<td>Not spec., one year</td>
</tr>
<tr>
<td>Askari and Ameri (2009)</td>
<td>Not specified</td>
<td>Lead-acid</td>
<td>PV system and storage size</td>
<td>Cost of electricity</td>
<td>No/No</td>
<td>Not spec., one year</td>
</tr>
<tr>
<td>Bost et al. (2011)</td>
<td>Crystalline silicon (mono)</td>
<td>Lithium-Ion</td>
<td>PV system and storage size, technology cost, consumption pattern</td>
<td>Cost of electricity, Grid Parity</td>
<td>Yes/Yes</td>
<td>2010-2020</td>
</tr>
<tr>
<td>Braun et al. (2009)</td>
<td>Crystalline silicon (mono)</td>
<td>Lithium-Ion</td>
<td>Storage size, electricity price, technology cost, FIT regression rate</td>
<td>IRR, payback period</td>
<td>Yes/Yes</td>
<td>2010, 2014</td>
</tr>
<tr>
<td>Celik et al. (2008)</td>
<td>Crystalline silicon (mono)</td>
<td>Lead-acid</td>
<td>PV system size, location</td>
<td>Cost of electricity</td>
<td>No/No</td>
<td>Not spec., one year</td>
</tr>
<tr>
<td>Clastres et al. (2010)</td>
<td>Crystalline silicon (poly)</td>
<td>Not specified</td>
<td>Consumption pattern</td>
<td>Profit</td>
<td>No/No</td>
<td>Not spec., one year</td>
</tr>
<tr>
<td>Colmanas-Santos et al. (2012)</td>
<td>Not specified</td>
<td>Lead-acid</td>
<td>PV system and storage size</td>
<td>IRR, payback period</td>
<td>Yes/No</td>
<td>2011</td>
</tr>
<tr>
<td>Denholm and Margolis (2007)</td>
<td>Not specified</td>
<td>Not specified</td>
<td>PV system and storage size</td>
<td>Cost of electricity</td>
<td>No/No</td>
<td>Not spec., one year</td>
</tr>
<tr>
<td>Jallouli and Krichen (2012)</td>
<td>Not specified</td>
<td>Not specified</td>
<td>Storage size</td>
<td>Cost of electricity</td>
<td>No/No</td>
<td>Not spec., one year</td>
</tr>
<tr>
<td>Kaldellis et al. (2009)</td>
<td>Not specified</td>
<td>Lead-acid, sodium-sulfur</td>
<td>PV system size, energy autonomy, solar irradiation, discount rate, investment subsidy, electricity price</td>
<td>Cost of electricity</td>
<td>No/No</td>
<td>Not spec., one year</td>
</tr>
<tr>
<td>Kolic (2009)</td>
<td>Not specified</td>
<td>Not specified</td>
<td>PV system and storage size, technology cost</td>
<td>Cost of electricity</td>
<td>No/No</td>
<td>Not spec., one year</td>
</tr>
<tr>
<td>Kolic et al. (2002)</td>
<td>Not specified</td>
<td>Lead-acid</td>
<td>Discount rate, solar irradiation, technology cost, O&amp;M costs</td>
<td>Cost of electricity</td>
<td>No/No</td>
<td>Not spec., one year</td>
</tr>
<tr>
<td>Li et al. (2009)</td>
<td>Crystalline silicon (poly)</td>
<td>Lead-acid</td>
<td>PV system size, technology cost, component efficiency</td>
<td>Cost of electricity</td>
<td>No/No</td>
<td>Not spec., one year</td>
</tr>
<tr>
<td>Liu et al. (2012)</td>
<td>Thin-film</td>
<td>Lead-acid</td>
<td>PV system and storage size, PV panel slope, technology cost and life-time, electricity price</td>
<td>Cost of electricity, net present cost</td>
<td>Yes/No</td>
<td>Not spec., one year</td>
</tr>
<tr>
<td>Wissem et al. (2012)</td>
<td>Crystalline silicon (mono &amp; poly)</td>
<td>Lead-acid</td>
<td>PV system and storage size, PV panel slope</td>
<td>Cost of electricity</td>
<td>No/No</td>
<td>Not spec., one year</td>
</tr>
</tbody>
</table>

* FIT: Feed-in Tariff  ** SC: Self-Consumption
Both studies by Bost et al. (2011) and Braun et al. (2009) test for potential influences of a number of input parameters on profitability and provide interesting insights into the potential future profitability of storage. Yet, two questions remain open from these analyses. First, in both studies it is assumed that the household receives a premium paid on top of electricity market prices for PV-generated electricity that is self-consumed or fed it into the grid. This assumption reflects the current regulatory situation in the German energy market under the Renewable Energy Sources Act, which Bost et al. (2011) and Braun et al. (2009) investigate. However, both the feed-in premiums and self-consumption incentives paid have been subject to considerable change in the recent years (Hoppmann et al., 2012). The feed-in tariff for PV has fallen by more than 43 percent from 2009 to 2011 and has already reached a level that is below average retail prices. PV will have to compete in a market with other sources of electricity without policy support in the foreseeable future. Under a regime with no demand-side policy support storage profitability will strongly depend on market electricity prices. In their studies Bost et al. (2011) and Braun et al. (2009) consider different electricity retail price developments. However, as they assume the existence of FITs, they do not investigate the effect of different wholesale price scenarios and the possibility of the household having limited access to the wholesale market.

Second, whereas the majority of studies listed in Table 1 explicitly optimize the size of both the PV system and the storage for a given electricity consumption to achieve a minimum cost of electricity, this is not the case for Bost et al. (2011) and Braun et al. (2009). Systematically testing for a wider range of different PV-storage-combinations is important since the self-consumption ratio, and hence the financial return of the storage investment, is highly sensitive to the assumed PV and storage size. Choosing the PV system sufficiently small can lead to very high self-consumption ratios even without storage since beyond a certain point almost all supply is backed by household demand. Accordingly, Bost et al. (2011) themselves point out that, while the size of PV plants in Germany has risen over the last years, increasing incentives to self-consume PV electricity (due to falling FITs and additional self-consumption incentives) may lead to a trend towards smaller PV plants. Currently, however, it remains unclear to which extent economic optimization of PV system and storage size affects the profitability of storage over time. In particular, it appears interesting to investigate whether and when economic optimization of PV system and storage size allows operating storage profitably in an environment without policy support.

\(^3\) In their model, Braun et al. (2009) only vary the storage size and keep the PV system size constant. Bost et al. (2011) simulate different sizes of both the PV system and storage but do not systematically optimize these two parameters with regard to an economic objective function.
3 Data and Method

In the subsequent sections, we explain the design and input parameters of our techno-economic model. Following the general logic depicted in Figure 1, we first describe the system layout and boundaries (Section 3.1). Next, in Section 3.2 the technological and economic input parameters of the model are presented, including the eight electricity price scenarios we employ. We provide a detailed explanation of the different modules of the model and discuss how they interact to produce the simulation results in Section 3.3. The model output and the sensitivity analysis we conducted are described in Section 3.4.

Figure 1: Overview of model structure
3.1 System Boundaries and Layout

To investigate the economic viability of storage in distributed PV systems, we simulate electricity generation and consumption for a three-person household in Stuttgart, Germany. Similar to the studies by Bost et al. (2011) and Braun et al. (2009), Germany was chosen as a country as it has the largest share of PV in its electricity mix and operates more than 35 percent of the worldwide installed PV capacity. The resulting intermittency in electricity generation makes Germany a potentially important market for storage solution providers (EPIA, 2012). Although, due to falling prices for PV systems, the average size of PV plants in Germany has constantly risen over the years, a large share of the German PV market is still made up of small-scale, residential PV systems. For example, of the more than 73,000 PV plants installed in Germany from January to April 2012, more than 47% had a size of less than 10 kWp and more than 85% a capacity of less than 30 kWp (Bundesnetzagentur, 2012). A three-person household was chosen to make the results of this study comparable to previous studies of PV systems in Germany, which have usually investigated households of similar sizes.

The layout of the integrated PV-storage system to be investigated is shown in Figure 2. It consists of the PV system, battery storage, two DC-AC inverters and an AC bus. This system layout is the most widely used one in the literature, considered economically efficient and suitable for domestic applications and producing minimal losses (Jenkins et al., 2008, Castillo-Cagigal et al., 2011, Sauer et al., 2011). The detailed mode of operation of the system as assumed in our model will be described in Section 3.3.

3.2 Model Input Parameters

3.2.1 Technological Input Parameters

The technological input parameters can be broadly divided into three categories: those pertaining to electricity generation, the electricity storage and the electric load. In the following, each of the categories will be discussed separately.

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4 The electricity generated by the PV system is inverted and transmitted to an AC bus where it can either be directly assigned to the loads of the household (right), stored in the storage (bottom) or transmitted to the grid (left). To store electricity, the electricity fed into the storage is tapped from the AC bus, inverted to DC and stored. When the household needs to access electricity from the storage, the DC power in the battery is re-inverted to AC and fed into the household through the AC bus.
Electricity Generation

The PV electricity production in kWh per kWp is a function of the available global horizontal solar irradiation, the outside air temperature as well as the tilt, orientation and performance characteristics of the PV module. Hourly solar irradiation data for Stuttgart, Germany, was obtained from the EnergyPlus weather database provided by the U.S. Department of Energy (2011). Orientation and tilt were chosen such that the PV modules could operate under optimal conditions. In southern Germany, this corresponds to a southward orientation and a tilt of 30° (Peters et al., 2011).

In line with previous studies (see Section 2) we choose crystalline silicon as a PV technology. This choice is made as currently crystalline silicon PV offers higher conversion efficiencies than thin-film PV and therefore has a market share in residential markets that exceeds 86% (Photon, 2012). To reflect inefficiencies in the PV system, such as inversion losses, the PV system rated output is multiplied with a performance ratio (PR) of 85%.5 In sum, the chosen parameters lead to an annual electricity generation of 980.93 Wh/kWp.

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5 We deliberately choose a slightly higher value than the average PR of 84% found by Reich et al. (2012) as we separately account for losses due to temperature and degradation. In line with Jordan et al. (2010) module efficiency decreases at a rate of 0.5% per year. The temperature coefficient was chosen to be 97.8% (Peters et al., 2011).
Electricity Storage

Similar to the majority of previous studies (see Section 2), we choose lead-acid batteries as the storage technology for our model. Compared to other battery technologies, lead-acid batteries have a short lifetime and low energy and power density. However, currently, due to their high reliability, low self-discharge as well as low investment and maintenance costs, they are the dominant technology in small scale, residential applications (Jenkins et al., 2008, Sauer et al., 2011, Nair and Garimella, 2010). Several authors argue that in the longer-term lead-acid could be replaced by lithium-ion batteries that possess better ageing features and a higher energy efficiency (Braun et al., 2009, Divya and Østergaard, 2009, VDE, 2009). At present, however, lithium-ion batteries are still in a relatively early phase of development and 3.5 times as expensive as lead-acid (Sauer et al., 2011). Furthermore, in the case of stationary use, the lower energy and power density of lead-acid batteries are not as critical as, for example, in electric mobility. Based on a comprehensive literature review (see Table A.1 in appendix), the round-cycle efficiency of the battery system was set to 81% and the self-discharge per day to 0.03%.

Electric Load Profile

We use standard load profiles for household electricity consumption in Germany at a resolution of 15 minutes (E.ON Bayern, 2012). The load profile was scaled to an annual consumption of 3.908 kWh to reflect the pattern of a three-person household in Germany (Bost et al., 2011). Moreover, to be consistent with the electricity consumption profile, the data was transformed from a resolution of 15 minutes to one hour by adding up the value within every hour. Figure 3 juxtaposes the resulting electricity load with electricity generation for the case that annual electricity generation of the PV system equals the annual consumption of the household. It becomes apparent that without storage there is a strong mismatch between the electricity produced and generated which varies over the year.

3.2.2 Economic Input Parameters

In the following we present the economic input parameters of the model. We first review some general assumptions and discuss the assumptions regarding the costs of the PV system, the battery system and electricity prices. It is important to note that, while we conducted a comprehensive review of previous studies and market data to identify the input values for our model, often the range of possible values remains relatively broad. For this reason we use 8 scenarios for electricity
prices. In addition, we performed a sensitivity analysis to test the robustness of the model against changes in the other input parameters (see Section 3.3).

Figure 3: PV electricity generation vs. electric load over year for annual consumption equaling annual production without storage

**General Assumptions**

Since we are modeling a household in southern Germany, we choose Euro as the currency and assume inflation to be the one of the Euro zone, i.e., 2.1% (eurostat, 2013). Based on a review of previous studies, 4% is chosen as a value for the nominal discount rate.

**Photovoltaic System Cost**

Table 2 lists the model input parameters related to the PV system costs that were retrieved from the literature, annual reports of PV module producers, industry reports and expert interviews. To obtain a proxy for module and inverter manufacturing costs, we scanned the annual reports of 10 companies producing solar photovoltaic modules\(^6\) and subtracted the firm’s profit per unit sold before interest and taxes (EBIT) from their 2011 average module sales price. The cost estimates

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\(^6\) Companies included in the analysis were Suntech Power, Yingli Green Energy, JA Solar, Trina Solar, Canadian Solar, Hanwha Solar One, China Sunergy, Jinkosolar, Renewable Energy Corporation (REC) and LDK Solar.
were then weighted by the corresponding market share of the company, leading to an average manufacturing cost including overhead of 1.16 EUR/Wp in 2011.\textsuperscript{7}

To be able to assess the economic viability of storage for distributed PV in the future, we applied a learning curve approach that allows estimating future investment costs based on the cumulative global deployment of PV. The learning rates used for the PV module, inverter and balance of system (BOS) are listed in Table 2, data for future PV deployment is obtained from EPIA (2012) (see Figure A.1 in the appendix).\textsuperscript{8} Figure 4 exemplarily shows the resulting PV investment cost for 2011, 2015 and 2020.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Assumed PV investment costs (nominal) in EUR/Wp}
\end{figure}

\begin{table}
\centering
\begin{tabular}{|c|c|}
\hline
Year & Learning rate\% \\
\hline
2011 & 8\% \\
2015 & 10\% \\
2020 & 12\% \\
\hline
\end{tabular}
\caption{Learning rates for PV module, inverter and BOS}
\end{table}

\textsuperscript{7} It should be noted that, in fact, the average sales price in 2011 was below this calculated cost level since the majority of companies producing PV modules sold below costs. Since we are interested in a longer-term estimate of sales prices, however, for our model we assume that in the long-term companies have to operate at a positive EBIT margin.

\textsuperscript{8} We take the average of EPIA’s (2012) ‘moderate’ and ‘policy-driven’ scenarios in which PV deployment grows at an annual rate of 32\% and 43\% respectively. Given that deployment rates in the PV industry have been highly volatile, ranging from 15.34\% in 1996 to 76.2\% in 2011, these two scenarios cannot cover the entire range of possible PV deployment in the short-term. Considering that PV deployment since 1994 has grown at an average rate of 35\%, however, they represent reasonable long-term scenarios that allow studying the profitability of storage as a function of PV deployment.
Table 2: Economic input parameters for PV system

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV module</td>
<td>Manufacturing cost 2011 (incl. overhead)</td>
<td>1.16 EUR/Wp</td>
<td>Annual reports of module manufacturers</td>
</tr>
<tr>
<td></td>
<td>Learning rate PV module</td>
<td>20%</td>
<td>Kost and Schlegl (2010)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wand and Leuthold (2011)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Junginger et al. (2010)</td>
</tr>
<tr>
<td></td>
<td>EBIT margin</td>
<td>10%</td>
<td>Expert interview</td>
</tr>
<tr>
<td></td>
<td>Module lifetime</td>
<td>25 years</td>
<td>See Table A.3 in appendix</td>
</tr>
<tr>
<td>Inverter</td>
<td>Manufacturing cost (incl. overhead)</td>
<td>0.19 EUR/Wp</td>
<td>Annual reports of SMA AG</td>
</tr>
<tr>
<td></td>
<td>Learning rate inverter</td>
<td>18%</td>
<td>Annual reports of SMA AG, own calculation</td>
</tr>
<tr>
<td></td>
<td>EBIT margin</td>
<td>15%</td>
<td>Annual reports of SMA AG, expert interview</td>
</tr>
<tr>
<td></td>
<td>Inverter lifetime</td>
<td>15 years</td>
<td>EPIA (2011)</td>
</tr>
<tr>
<td>Balance of systems</td>
<td>Sales price BOS PV system 2011</td>
<td>0.61 EUR/Wp</td>
<td>BSW Solar (2012)</td>
</tr>
<tr>
<td></td>
<td>Learning rate BOS PV system</td>
<td>18%</td>
<td>Schaeffer (2004)</td>
</tr>
<tr>
<td>EPC* &amp; operations and maintenance</td>
<td>EPC* PV system</td>
<td>8% of PV system cost (incl. inverter)</td>
<td>Peters et al. (2011)</td>
</tr>
<tr>
<td></td>
<td>Operations and maintenance cost PV</td>
<td>1.5% of PV system cost (incl. inverter) per year</td>
<td>Peters et al. (2011)</td>
</tr>
</tbody>
</table>

* EPC: Engineering, procurement and construction

**Electricity Storage Cost**

The economic parameters for lead-acid storage used in our model are summarized in Table 3. The battery investment cost is calculated by adding up the energy and a power cost of 150 EUR/kWh and 175 EUR/kW respectively (see Table A.4 in appendix). This procedure was recommended by experts we consulted on this issue. While studies differ considerably with regard to their assessment of future cost decreases, it has been pointed out that, in general, lead-acid batteries still offer significant potential for cost improvements. Therefore, in line with VDE (2009), a constant decrease in battery investment costs of 7.6% per year is assumed. In accordance with the literature, balance of system (BOS) costs are calculated as a fixed share of one third of the battery cost. Furthermore, similar to the PV system, inverter costs are modeled as a function of the maximum power input to or output of the storage. The resulting investment costs for the storage system are displayed in
Figure 5. Since the battery is assumed to have a life time of 8.3 years, it is replaced twice during the life of the PV system.

Table 3: Economic input parameters for battery storage system

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>Battery investment costs in 2011</td>
<td>150 EUR/kWh + 175 EUR/kW</td>
<td>See Table A.4 in appendix</td>
</tr>
<tr>
<td></td>
<td>Battery investment cost decrease</td>
<td>-7.6% per year</td>
<td>VDE (2009)</td>
</tr>
<tr>
<td></td>
<td>Battery life time</td>
<td>8.3 years</td>
<td>See Table A.4 in appendix</td>
</tr>
<tr>
<td>Inverter</td>
<td>See Table 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balance of systems</td>
<td>BOS storage</td>
<td>1/3 of battery cost</td>
<td>See Table A.5 in appendix</td>
</tr>
<tr>
<td>EPC and operations and</td>
<td>EPC battery system</td>
<td>8% of battery system cost (incl. inverter)</td>
<td>See Table 2</td>
</tr>
<tr>
<td>maintenance</td>
<td>Operations and maintenance cost battery</td>
<td>5 EUR/kW per year</td>
<td>Schoenung and Hassenzahl (2003)</td>
</tr>
</tbody>
</table>

Figure 5: Investment costs (nominal) for 5kWh storage for annual PV electricity generation equaling annual household consumption
Electricity Prices

As discussed in Section 2, the economic viability of storage in a regime without policy support is likely to be strongly affected by the present and future level of retail and wholesale electricity prices. According to BDEW (2012), the average retail price in Germany in 2011 amounted to 0.2523 EUR/kWh.9 As a wholesale price we chose 0.059 EUR/kWh. The latter value was derived from EPIA (2011) and constitutes the average wholesale price during peak hours, i.e., weekdays from 8 a.m. to 8 p.m. Since the time of PV net electricity production falls into this time range, the price was considered a valid starting point for our analysis.

The future development of both wholesale and retail electricity prices is highly uncertain. To evaluate a range of possible developments in our model, we applied eight electricity price scenarios (see Table 4).

Table 4: Electricity price scenarios used in model simulations

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Assumption</th>
<th>Electricity Wholesale Price Scenario</th>
<th>Electricity Retail Price Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Unlimited access of household to wholesale market</td>
<td>High: +3% per year (real)</td>
<td>High: +2% per year (real)</td>
</tr>
<tr>
<td>S2</td>
<td>Unlimited access of household to wholesale market</td>
<td>Low: -1% per year (real)</td>
<td>High: +2% per year (real)</td>
</tr>
<tr>
<td>S3</td>
<td>Medium: +1.5% per year (real)</td>
<td>Medium: +1% per year (real)</td>
<td></td>
</tr>
<tr>
<td>S4</td>
<td>High: +3% per year (real)</td>
<td>Low: -1% per year (real)</td>
<td></td>
</tr>
<tr>
<td>S5</td>
<td>No access of household to wholesale market</td>
<td>Constant: 0 EUR/kWh</td>
<td>High: +2% per year (real)</td>
</tr>
<tr>
<td>S6</td>
<td>No access of household to wholesale market</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S7</td>
<td>Medium: +1% per year (real)</td>
<td>Low: +0% per year (real)</td>
<td></td>
</tr>
<tr>
<td>S8</td>
<td>Low: +0% per year (real)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The first five scenarios (S1 to S5) assume that the household has unlimited access to the wholesale market and contain three possible developments for each wholesale and retail prices. In scenarios S2 and S5 wholesale prices are assumed to fall, which would reflect the current observation that an increasing supply of renewable electricity sources with low variable costs tends to lower wholesale prices (so-called ‘merit order effect’). However, due to the intermittent nature of the former

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9 In accordance with the majority of private electricity contracts in Germany, we assume that the retail price is the same for the entire day, i.e., there is no special night tariff.
technologies a change in the structure of the entire electricity market might become necessary to incentivize the provision of additional, flexible capacity with higher variable cost (e.g., through so-called ‘capacity markets’). As the latter might lead to rising, rather than falling wholesale prices, we include scenarios in which wholesale prices rise by 1.5% (S3) and 3% annually in real terms (S1 and S4). Apart from electricity generation cost, retail prices in Germany include grid fees, the utility’s profit margin, taxes and the ‘EEG apportionment’, the latter containing the cost of the feed-in tariff that is redistributed to the consumer. The increasing deployment of renewables in Germany is likely to raise retail prices in the foreseeable future through the EEG apportionment and additional investments in the electricity grid. Since the exact amount of increases in retail prices are uncertain, based on a review of literature (see Table A.6), we investigate three possible developments, namely real increases of 2% (scenarios S1 and S2), 1% (scenario S3) and 0% (scenarios S4 and S5).

Currently, it remains uncertain to what extent households will be able to directly sell their electricity on the wholesale electricity market. Moreover, wholesale prices fluctuate considerably during the day with dips occurring when many renewable plants simultaneously feed in their electricity, e.g., during noon. To consider these possibilities, we test three extreme scenarios at which wholesale prices are assumed to be 0 EUR/kWh (S6 to S8). Since we model investment decisions from 2011 to 2020 for a PV system with a lifetime of 25 years, electricity prices are extrapolated until 2045 in all eight scenarios. Compared to previous studies, our maximum price increases are chosen rather conservatively. Nevertheless, it should be noted that under our assumptions in the high price scenarios, retail and wholesale price in 2045 reach a level of 0.4947 EUR/kWh and 0.1612 EUR/kWh in 2011 prices respectively (see Figure A.2 in the appendix).

### 3.3 Techno-Economic Model of Integrated PV-Storage-System

The following sections describe how the values are processed in the model to generate our results. We first present the three main modules of the model – 1) the self-consumption calculation module, 2) the net present value calculation module and 3) the storage and PV size optimization module.

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10 In the short term, the assumption that households can sell their electricity on the wholesale market requires a preferential feed-in of PV as established under the German Renewable Sources Act since the handling of a large number of intermittent electricity sources on the market is difficult. In the longer-term, when electricity costs of solar PV have fallen further and intermediary institutions have been established that bundle and market solar PV power, it seems possible that solar PV can be marketed on the wholesale market without preferential treatment.
**Self-Consumption Calculation Module**

As the basis for the economic calculations, in a first step the self-consumption ratio (SCR), i.e., the share of electricity generated by the PV system that is consumed by the household, is calculated. Figure 6 portrays the general logic underlying the calculation. It is assumed that whenever electricity demand during the day can be met by the concurrent electricity generation of the PV system, the household consumes its own electricity (see number 4 in Figure). If electricity generation exceeds household consumption, electricity is either stored for later consumption (2) or sold to the grid if the storage is loaded (3). The ratio between electricity that is directly self-consumed (4) or taken from storage later (5) and the total electricity generated by the PV system (2+3+4) defines the self-consumption ratio. For a given electricity consumption, this ratio is directly dependent on the size of the PV system and the size of the battery storage. In the model, the self-consumption ratio is calculated by simulating the electricity flows of the system over the year at an hourly resolution. The self-consumption ratio serves as an input to the second module of the model which calculates the net present value of the integrated PV-battery system for the household.

![Figure 6: General logic of self-consumption calculation module](image-url)
**Net Present Value Calculation Module**

For a given investment year \( t \), the net present value (NPV) of household investments is calculated as the sum of the discounted cash in- and outflows over the 25 year lifetime of the PV/battery system.\(^{11}\) As shown in detail in appendix B, cash outflows comprise the investment costs for the PV system and battery system as well as the operations and maintenance expenses (see Section 3.2). For the cash inflow it is assumed that with consuming electricity from the own PV system, the household substitutes electricity that it would otherwise have to purchase from the electric utility at retail prices. Excess electricity that is neither self-consumed nor stored is sold at wholesale prices. The revenues of the household are then calculated as the sum of 1) the self-consumed electricity (i.e., the product of electricity generated during each year of system lifetime multiplied and the SCR) multiplied with the retail electricity price and 2) the electricity sold (i.e., the product of the electricity generated during each year of system lifetime and 1-SCR) multiplied with the wholesale electricity price.

**Storage and PV System Size Optimization Module**

The third module draws on the inputs from the “Self-Consumption Calculation Module” and the “Net Present Value Calculation Module” to find the optimal storage and PV system size for the household. For each investment year from 2011 to 2020 and each of the eight electricity price scenarios (see Table 4 in Section 3.2) the module calculates the net present value for 1,435 different combinations of PV system and storage sizes (35 PV system sizes times 41 storage sizes). Based on these values, the PV system and storage size are identified that maximize the NPV of the overall PV-storage system (see appendix C for a more detailed description of the calculation procedure). Tested PV system sizes range from 0.4 kW\(_p\) to 14 kW\(_p\) and are incremented at steps of 0.4 kW\(_p\). 14 kW\(_p\) was chosen as the maximum since the PV capacity that can be installed on village houses in Germany was, on average, found to be limited to this value (Lödl et al., 2010). The storage sizes tested by the model range from 0 kWh (i.e., no storage) to 20 kWh and are increased at intervals of 0.5 kWh. Note that the model assumes a depth of discharge of the battery of 80%, i.e., the usable battery capacity is lower than the nominal values indicated.

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\(^{11}\) Since in Germany, households have access to low-interest loans from ‘KfW bank’, in general the availability of capital does not constrain the size of PV systems and storage to be invested in. As a result, the households can be considered to maximize the absolute return from the integrated PV-storage system, irrespective of its size. In our model, we therefore use (and maximize) the NPV as a measure of profitability.
3.4 Model Output and Sensitivity Analysis

Overall, for each investment year from 2011 to 2020 and each of the eight electricity price scenarios the model generates three main outputs:

1) The economically optimal size of the PV system,
2) the economically optimal size of the storage system and
3) the profitability of the storage investment.

As described in the previous Section, the optimal PV system and storage size are those that maximize the NPV of the integrated PV-storage system. As a measure for profitability of the storage investment, we use the profitability index (PI) which is defined as the quotient of the NPV of the storage investment and the storage investment cost at the time of investment.\(^{12}\)

To investigate the robustness of the model with regard to variations in the input parameters, a sensitivity analysis was conducted. As part of this analysis the 12 most important input parameters that had not been modeled as scenarios were augmented and lowered by 33% of their original value one at a time for scenario S3 (which assumes medium increases of both retail and wholesale price). The results of this analysis will be presented in Section 4.4 after describing the general simulation results.

4 Results

In the following, we describe the model outcomes, i.e., a) the optimal PV system size, b) the optimal size of storage and c) the profitability of storage for a rationally optimizing household for the years of investment from 2011 to 2020 and the eight electricity price scenarios.

4.1 Optimal PV System Size

The development of the optimal PV system size as well as the corresponding electricity production/consumption ratio for an economically rational household under the 8 electricity price scenarios is shown in Figures 7 and 8. The production/consumption ratio describes the quotient of

\(^{12}\) We use the profitability index to measure storage profitability instead of the NPV since we optimize the storage size for different points in time of investment. The differences in optimal storage size over time would make the profitability of storage hard to compare if we used an absolute measure of profitability. Therefore, we report the storage profitability as the NPV per EUR invested. The optimal storage size over time is reported as a separate output variable.
the annual electricity generated by the PV system and the annual electricity consumption of the household.

As can be seen, under a medium electricity retail price, medium electricity wholesale price scenario (S3) the optimal size of the PV system the household invests in rises strongly over time. Most importantly, investments in the PV system are profitable for the household through the period of investigation, which is indicated by the fact that the size of the PV system is always different from zero. In early years, however, the optimal PV system size is chosen such that the PV system generates less electricity than the household consumes (i.e., the production/consumption ratio is smaller than 1). This is due to the fact that investment costs for both the PV and the storage system are relatively high, requiring the household to have a high rate of direct self-consumption which can only be reached when choosing a small PV system size. With falling investment costs, however, the optimal production to consumption ratio increases to reach a point where after 2014 annual PV electricity generation exceeds the electric load of the household. Subsequently, the optimal PV system rises further until in 2019 under the S3 scenario its size reaches the maximum PV system size of 14 kWp.

As shown in scenarios S1, S2, S4 and S5 in Figure 7, the optimal PV plant size is very sensitive to both future retail and wholesale electricity prices. Stronger increases in retail prices (scenarios S1 and S2) favor larger PV plant sizes since they enhance the value of the electricity produced by the PV system – which substitutes electricity purchased from the grid. Similarly, for a given retail price scenario, the optimal PV system size is higher for higher wholesale prices (S1 and S4) since excess electricity can be sold on the market at higher prices. Interestingly, while retail prices are the factor that influences PV system size most strongly in early years, wholesale prices become more important during the later periods. This can be explained by the fact that with falling technology costs, the size of PV plants rises over time which leads to a situation where households, despite using storage, need to sell an increasing share of their electricity on the wholesale market. Under the assumption that the household does not have access to the wholesale market, the optimal PV system size is considerably smaller than the one for scenarios where the household can not only consume but also sell its electricity (see S6 to S8 in Figure 8). As could be expected, the household chooses the PV system size such that the electricity it produces almost never exceeds the electricity the household consumes.

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13 It should be emphasized that our finding that already in 2011 PV systems in Germany were profitable without policy support hinges on a number of assumptions: a) The household needs to optimize the size of the PV system since only small systems are profitable in early years, b) electricity prices need to develop as indicated in our scenarios and c) costs for engineering, procurement and construction depend mostly on the size of the system (i.e., they do not contain a large fixed component which may be the case for very small PV systems).
Figure 7: Optimal PV plant size under electricity price scenarios S1 to S5

Figure 8: Optimal PV plant size under the assumption of no access to the electricity wholesale market (electricity price scenarios S6 to S8)
4.2 Optimal Storage Size

Figures 9 and 10 display the development of the optimal storage size. Under the medium electricity retail price, medium electricity wholesale price scenario (S3), the optimal storage size amounts to 3.5 kWh storage in 2012 and rises significantly to reach 7.5 kWh in 2020. The fact that the optimal storage size levels out is due to the fact that our model includes a constraint for the maximum PV system size which dampens the size of storage that is installed under economic considerations.

Similar to the optimal PV system size, the optimal storage size in early years depends particularly on the assumed retail price developments. Under the assumption of strong increases in future retail prices, the household invests in 3.5 to 4 kWh storage as early as 2011 (scenarios S1 and S2), whereas when assuming a stagnation in retail prices (real) no storage is added until 2013 or 2014 (scenarios S3 and S4). Interestingly, given a particular retail price increase, the optimal storage size is slightly larger for scenarios that assume a stronger increase in wholesale prices (see scenarios S1 vs. S2 and scenarios S4 vs. S5). At a first glance, this result seems counterintuitive since one might assume that storage becomes particularly important when wholesale prices are low such that a household does not have to sell electricity on the market at low prices. Yet, this finding can be explained by the fact that higher wholesale prices trigger investments in larger PV plants (see previous section), which in turn raises the optimal storage capacity. Overall, however, the impact of wholesale prices on the optimal storage size is relatively small. Even when assuming a constant wholesale price of 0 EUR (i.e., no possibility for households to sell their electricity on the wholesale market) the optimal storage is almost identical until 2017 to a scenario where the household can sell the electricity at a medium wholesale price (see scenarios S6 to S8 in Figure 10).
Figure 9: Optimal storage size under electricity price scenarios S1 to S5

Figure 10: Optimal storage size under the assumption of no access to the electricity wholesale market (electricity price scenarios S6 to S8)
4.3 Storage Profitability

The development of storage profitability over time (excluding the PV system) is shown in Figures 11 and 12. Under the medium electricity retail price, medium electricity wholesale price scenario (S3), including battery storage in the residential PV system becomes profitable in 2012. Furthermore, due to falling investment costs profitability of storage continuously rises over time in an almost linear fashion. Under the assumptions of our model, in the S3 scenario, the storage PI rises from 0 in 2011 to 2.23 in 2020.

Like the optimal storage size, storage profitability depends mostly on retail prices. Assuming a higher retail price scenario raises the profitability for all years under investigation (see scenarios S1 and S2), whereas a low retail price scenario lowers it (scenarios S4 and S5). Under the assumption of a stronger increase in future retail electricity prices, storage is profitable as early as 2011. Lower wholesale prices raise the profits to be gained from storage investments in later years when PV systems are large and households tend to sell a higher share of their electricity to the market (see scenarios S2 and S5). Correspondingly, investments in storage remain profitable even under the assumption of a constant wholesale price of 0 EUR, i.e., no access of households to wholesale markets (see scenarios S6 to S8 in Figure 12).

4.4 Sensitivity Analysis

Figure 13 shows a tornado graph on how the profitability index (i.e., the NPV of the storage investment per EUR invested in storage) changes when varying the most important input parameters, that are not covered by the scenarios, by -33% and +33%. It becomes obvious that of all input parameters, the nominal discount rate and the battery investment cost in 2011 have the greatest effect on the model outcome. Moreover, the model is sensitive to changes in the assumption of future battery cost decreases and the assumed increase in the global installed PV capacity (the latter determining the technological learning and hence the investment costs of PV).
Figure 11: Storage profitability under electricity price scenarios S1 to S5

Figure 12: Storage profitability under the assumption of no access to the electricity wholesale market (electricity price scenarios S6 to S8)
5 Discussion

In the following we discuss the implications of our findings for private households, the broader electricity sector and policy makers.

5.1 Implications for Household Investments

The findings presented in the previous section demonstrate that already now battery storage is economically viable for small PV systems if one assumes a strong increase in future retail prices. Under the assumptions of our model and supposing economic optimization, storage investments will be profitable under all electricity price scenarios as of 2014. Especially those scenarios that, in line with current trends in Germany, assume a decrease in electricity wholesale prices and a concurrent increase in electricity retail prices lead to a high economic viability of storage investments. Moreover, if households are assumed to have limited access to the wholesale market in the future, this does not undermine but may even bolster storage profitability.
The early profitability of storage for residential PV without policy support is striking and can be assumed to have a major impact on household investments. Nevertheless, we caution to conclude that a high profitability of integrated PV-storage systems will automatically imply a strong adoption of these technologies by households starting at this point in time. Despite being profitable, PV systems (with and without storage) may not be installed for several reasons. First, in stark contrast to investments under a feed-in tariff scheme, returns from investing in PV are much less certain under a regime without policy support. Given that market prices fluctuate significantly and the future development of both wholesale and retail prices remains unclear, future cash flows are difficult to predict. This is especially true if one considers that policy makers may take measures in the future that change the profitability of PV and storage investments. At the moment, for example, households in Germany that consume self-generated electricity do not have to pay electricity taxes, the EEG apportionment and grid fees. Since this puts an increasing burden on electricity consumers that do not own a PV system, it seems likely that policy makers will take measures to have owners of PV systems carry some of these costs in the future. Moreover, the individual load patterns of households deviate from the standard load pattern used in our analysis. In our analysis the household optimizes the size of both the PV and storage system to maximize its revenues. In reality, such optimization will be very hard to do as load patterns may be unknown or change over time and PV/storage systems will be offered in standardized sizes. The uncertainties regarding future electricity prices and difficulties in assessing the benefits from storage may prevent households from investing in PV and storage technologies. Second, apart from economic considerations, the adoption of PV and storage technologies by households strongly depends on social and environmental factors. Household investments are strongly driven by the knowledge about investment opportunities and the ability to overcome behavioral barriers. In addition, lead-acid batteries contain sulfuric acid and toxic lead which could hinder the wider penetration of this technology for residential PV systems due to social acceptance issues. Although in Germany nearly 100% of the lead in commercial-scale lead-acid batteries is recycled (VDE, 2009), it remains open whether lead-acid batteries find acceptance among the users of distributed PV systems, given that a significant share of them can be assumed to be particularly environmentally conscious.

5.2 Implications for the Electricity Sector

Besides providing insights into potential changes in household investments, our analysis has important implications for the electricity sector. As discussed in Section 4.1, it can be expected that even without policy support households will raise the amount of electricity they produce themselves. The use of battery storage supports this trend as it allows households to consume a larger share of
self-produced electricity, reducing the amount of electricity to be bought from utilities. Moreover, if households are also able to sell their electricity on the wholesale market in the future, an ever increasing number of households will move from being electricity consumers to becoming net electricity producers. This trend has the potential of fundamentally altering the existing market structure. Electric utilities are likely to be confronted with a growing number of households that produce and sell their own electricity which fundamentally undermines their current business model. At the same time, a shift towards a system of strongly distributed electricity generation will probably require major adaptations in the technical infrastructure of the electricity system, such as distribution grids. In fact, the observation that storage is economically viable for a private household does not imply that implementing battery storage systems is also beneficial from the perspective of overall stability of the electricity system. It currently remains open to what degree implementing small-scale, distributed storage reduces throughput and required capacity of the electricity grid. Hollinger et al. (2013) find that battery storage for residential PV systems can reduce the burden on the electricity distribution grids by around 40 percent. In contrast, Büdenbender et al. (2010) find no positive effect of storage on alleviating the stress on the distribution grid that is created by distributed PV. Some authors even argue that instead of enhancing grid stability, small-scale storage may add to instabilities (Sauer et al., 2011). It is suggested that, if storage solutions implemented are small, electricity feed-in patterns of PV systems could become less predictable with irregular peaks in distribution grids occurring when storages are loaded before noon.

5.3 Implications for Policy Makers

Finally, our results allow drawing some conclusions for policy makers. First, we find that residential PV systems of small sizes (with and without storage) are profitable without policy support under almost all scenarios in Germany in 2013. Nevertheless, policy support, e.g., in the form of feed-in tariffs may be necessary for at least an intermediary period since in an environment without policy support a) the PV systems that are built tend to be rather small, leading to a suboptimal use of roof-space and b) uncertainties and the inability of households to determine the profitability of PV systems may prevent households from investing (see Section 5.1).

Second, the findings of our analysis imply that additional economic incentives to foster the use of small scale storage in combination with residential PV systems in Germany appear necessary only in the short term. This result is of importance since several institutions in Germany, such as the German Solar Photovoltaic Industry Association (BSW), have called for additional incentives for battery storage in the past (Sauer et al., 2011). Recently, the German government has responded to
this call by announcing a 50 million EUR demonstration program that provides investment subsidies to buyers of storage for residential PV system (Photon, 2013). Our findings indicate that the incentives provided under this program can be phased out relatively soon as rising electricity retail prices and falling technology costs raise the profitability of storage.

Third, our findings allow deriving some insights into how different political interventions affect the economic viability of storage. In essence, all political measures that raise the retail price can be expected to also raise the profitability of storage investments for residential PV in the short-term. In the longer-term, measures that lower the wholesale price can additionally contribute to increasing the NPV from storage investments. In this sense, electricity taxes and grid fees that are only included in retail and not wholesale prices will provide an incentive for households to invest in storage technologies. Premiums for self-consumption will generally raise the profitability of storage investments. From the sensitivity analysis, it can further be derived that measures which reduce the investment cost of PV and storage, such as deployment policies or investments in R&D, contribute to enhanced storage profitability. Moreover, an important means for raising the profitability of investments in storage lies in lowering the interest rate at which households can obtain capital at financial markets. In this sense, low-interest loan programs, such as the KfW program in Germany, are likely to be very effective means at fostering storage investments. For measures like feed-in premiums, the effect on storage profitability is less clear since, on the one hand they raise the price at which households can sell the electricity on the market (negative effect on storage profitability). On the other hand, however, feed-in premiums increase the deployment of PV, potentially reduce wholesale prices in the longer term and may raise the retail prices in the short-term (positive effect on storage profitability – see Section 3.3). In Germany, FIT premiums have fallen significantly in the recent past while, simultaneously, the increasing use of renewables has raised retail and lowered wholesale prices. Interestingly, therefore, in Germany the policy-induced deployment of PV itself has driven the profitability of storage as a complementary technology.

6 Limitations and Future Research

Our study has several limitations that lend themselves as avenues for future research. First, as for any model, our results are limited by the input parameters chosen for our simulation. To keep the scope of the paper within reasonable boundaries, we restricted the choice of technologies to one PV and one battery technology. As described in Section 3, strong research and development efforts that

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14 Currently, the low-interest loans from the KfW bank are only available for PV systems. However, there are plans to introduce specific loan programs for storage which according to our analysis appears an effective way of fostering storage investments.
are currently being undertaken on other battery types (e.g., lithium-ion or sodium sulfur) could lead to significant cost decreases in the next years which would warrant a closer investigation of these technologies in residential PV applications. Moreover, assuming cost decreases in PV to follow the pattern of learning curves, of course, paints a simplified picture of technological change. While for our model the accuracy reached using learning curves is probably sufficient, a more detailed model of technological change would have to consider a wider range of drivers of technological change than deployment (Nemet, 2006) and should also take into consideration the rate at which technologies are deployed (Hoppmann et al., 2013). Since investment costs for technology, solar irradiation, electricity prices and electricity consumption patterns differ between countries (Schmidt et al., 2012), it would be valuable to repeat our analysis for households in other geographic locations. Furthermore, in future studies different household characteristics, such as the number of persons living in the household, should be varied to provide a more comprehensive picture of the economic viability of storage under different conditions. Ideally, when doing so, the resolution of the data regarding both, electricity generation and consumption, should be enhanced to account for short-term peaks that are leveled out when using hourly data. Although Wille-Haussmann (2011) finds that changing the resolution from 10s to 15 min values alters the self-consumption ratio only by 2 to 3%, a higher resolution becomes important when conducting a more detailed analysis of storage use for specific days, e.g., least or most sunny days during the year.

Second, we restrict our economic analysis to investigating how storage can be used to leverage the existing price spread between wholesale and retail prices. Beyond increasing self-consumption, however, storage can generate economic value in a range of different applications, such as ancillary services or arbitrage dealing, e.g., buying electricity at night and reselling it to the grid at daytime when electricity prices tend to be higher. Combining different applications can potentially further increase the economic viability of storage compared to the findings in this paper (Braun and Stetz, 2008). In this context, it should be kept in mind that in our model we assume the electricity consumption of the household to be invariant to electricity prices. It seems likely that in reality, especially with the emergence of demand-side management systems, households may alter their consumption pattern depending on the prices they face.

7 Conclusion

In this paper we investigate when and under which conditions battery storage will be economically viable in residential PV systems without policy support. Building upon a review of previous studies on the economics of battery storage for distributed PV, we develop a techno-economic model that
simulates the profitability of battery storage from 2011 to 2020 under eight different scenarios for PV investment costs and electricity prices in Germany. In contrast to previous forward-looking studies, we assume that no feed-in or self-consumption premium is paid for electricity generated using solar PV. Moreover, for each year of investment and each scenario, our model tests more than 1,400 combinations of PV system and storage size to determine the one that yields the highest net present value. We find that, given an economically rational household, investments in battery storage are already profitable for small residential PV systems if one assumes retail prices to increase more strongly in the future. The optimal PV system and storage sizes rise significantly over time such that in our model households become net electricity producers between 2015 and 2018 if they are provided access to the electricity wholesale market. Developments that lead to an increase in retail or a decrease in wholesale prices further contribute to the economic viability of storage. Under a scenario where households are not allowed to sell excess electricity on the wholesale market, the economic viability of storage for residential PV is particularly high. Our findings have important implications for the electricity sector and regulators that wish to shape its future. We conclude that, under the assumptions of our model additional policy incentives to foster investments in battery storage for residential PV in Germany seem necessary only in the short-term. At the same time, the increasing profitability of integrated PV-storage-systems may come with major challenges for electric utilities and is likely to require increased investments in technical infrastructure that supports the ongoing trend towards distributed electricity generation.
References


E.ON Bayern (2012). BDWE Standardlastprofile (SLP) H0 (Haushalte).


Appendix A

Table A.1: Overview of lead-acid technology parameters in the literature

<table>
<thead>
<tr>
<th>Author (year)</th>
<th>Self-discharge [% per day]</th>
<th>Roundcycle efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burke et al. (2007)</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Chen et al. (2009)</td>
<td>0.1-0.3</td>
<td>70-90</td>
</tr>
<tr>
<td>Divya and Østergaard (2009)</td>
<td>0.06-0.17</td>
<td>72-78</td>
</tr>
<tr>
<td>Dunn et al. (2011)</td>
<td></td>
<td>75-90</td>
</tr>
<tr>
<td>EPRI and DOE (2003)</td>
<td>0.033</td>
<td>75-85</td>
</tr>
<tr>
<td>Gonzalez et al. (2004)</td>
<td></td>
<td>81</td>
</tr>
<tr>
<td>Hadjipaschalis et al. (2009)</td>
<td>2</td>
<td>85-90</td>
</tr>
<tr>
<td>Sauer et al. (2011)</td>
<td></td>
<td>80-90</td>
</tr>
<tr>
<td>Schoenung and Hassenzahl (2003)</td>
<td>0.1</td>
<td>70-80</td>
</tr>
<tr>
<td>VDE (2009)</td>
<td></td>
<td>80-90</td>
</tr>
<tr>
<td>Wu et al. (2002)</td>
<td></td>
<td>80</td>
</tr>
</tbody>
</table>

Figure A.1: Global PV deployment underlying the PV investment cost development
### Table A.2: Overview of interest rates in the literature

<table>
<thead>
<tr>
<th>Author (year)</th>
<th>Interest Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMU (2007)</td>
<td>5-8%</td>
</tr>
<tr>
<td>Branker et al. (2011)</td>
<td>4.5%</td>
</tr>
<tr>
<td>Boet et al. (2011)</td>
<td>6%</td>
</tr>
</tbody>
</table>

### Table A.3: Overview of module lifetime parameters in the literature

<table>
<thead>
<tr>
<th>Author (year)</th>
<th>Module lifetime [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bhandari and Stadler (2009)</td>
<td>25-40</td>
</tr>
<tr>
<td>Denholm and Margolis (2007)</td>
<td>30</td>
</tr>
<tr>
<td>EPIA (2011)</td>
<td>25-35</td>
</tr>
<tr>
<td>Sauer et al. (2011)</td>
<td>20</td>
</tr>
<tr>
<td>Van der Zwaan and Rabl (2003)</td>
<td>25</td>
</tr>
</tbody>
</table>

### Table A.4: Overview of lead-acid lifetime and energy cost in the literature

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Chen et al. (2009)</td>
<td>5-15</td>
<td>143-286</td>
<td>214-428</td>
</tr>
<tr>
<td>Divya and Østergaard (2009)</td>
<td>50-150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dunn et al. (2011)</td>
<td>3-20</td>
<td>75-85</td>
<td></td>
</tr>
<tr>
<td>EPRI and DOE (2003)</td>
<td>5-10</td>
<td>143-207</td>
<td></td>
</tr>
<tr>
<td>Gonzalez et al. (2004)</td>
<td>5-15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hadjipaschalis et al. (2009)</td>
<td>5-15</td>
<td>36-71</td>
<td>164-250</td>
</tr>
<tr>
<td>Poompun and Jewell (2008)</td>
<td>218</td>
<td></td>
<td>130</td>
</tr>
<tr>
<td>Sauer et al. (2011)</td>
<td>6-12</td>
<td>80-200</td>
<td></td>
</tr>
<tr>
<td>Schoenung and Hassenzahl (2003)</td>
<td>5-6</td>
<td>129-257</td>
<td>107-214</td>
</tr>
<tr>
<td>VDE (2009)</td>
<td>6-12</td>
<td>100-300</td>
<td></td>
</tr>
</tbody>
</table>
Table A.5: Overview of storage BOS costs in the literature

<table>
<thead>
<tr>
<th>Author (year)</th>
<th>Reference unit</th>
<th>Share of reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gonzalez et al. (2004)</td>
<td>Power</td>
<td>16.6 - 25.2%</td>
</tr>
<tr>
<td>Poonpun and Jewell (2008)</td>
<td>Energy</td>
<td>41.7%</td>
</tr>
<tr>
<td>Schoenung and Hassenzahl (2003)</td>
<td>Power</td>
<td>20.0 - 90%</td>
</tr>
<tr>
<td>Schoenung and Eyer (2008)</td>
<td>Power</td>
<td>28.6%</td>
</tr>
</tbody>
</table>

Table A.6: Overview of electricity price forecasts for Germany in the literature

<table>
<thead>
<tr>
<th>Author (year)</th>
<th>CAGR retail price</th>
<th>CAGR wholesale price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bhandari and Stadler (2009)</td>
<td>2 - 4%</td>
<td>3 - 6%</td>
</tr>
<tr>
<td>EPIA (2011)</td>
<td>0.9%</td>
<td>4%</td>
</tr>
<tr>
<td>Roland Berger and Prognos (2010)</td>
<td>1.7%</td>
<td>3.2 - 5.1%</td>
</tr>
<tr>
<td>Nitsch et al. (2010)</td>
<td>0 - 2.5%</td>
<td></td>
</tr>
<tr>
<td>Nagl et al. (2010)</td>
<td>0 - 0.4%</td>
<td></td>
</tr>
</tbody>
</table>

Figure A.2: Assumed electricity price developments
Appendix B

The net present value of the integrated PV system is calculated as

\[ NPV_t = -C_t + \sum_{n=0}^{N} \frac{C_{IN,t,n} - C_{OUT,t,n}}{(1 + i)^n} \]

where

\[ C_t = CAPEX_{PV,t} + CAPEX_{BAT,t} + \frac{CAPEX_{BAT,t+9}}{(1 + i)^9} \]

\[ C_{IN,t,n} = [SCR_t \cdot RP_n + (1 - SCR_t) \cdot WP_n] \cdot kWh_t \cdot (1 - DR)^n \]

\[ C_{OUT,t,n} = OPEX_{PV,t,n} + OPEX_{BAT,t,n} \]

and

NPV: Net present value of integrated PV-storage system

\( t \): Year of investment (2011, ..., 2020)

\( n \): Year of system lifetime (0, ..., 25)

\( N \): System lifetime (25 years)

\( i \): Interest rate (4%)

\( C_{IN} \): Cash flow in

\( C_{OUT} \): Cash flow out

SCR: Self-consumption ratio

RP: Retail price

WP: Wholesale price

kWh: Electricity generated by PV system

DR: Module degradation rate

CAPEX\(_{PV}\): Capital investment cost PV system

CAPEX\(_{BAT}\): Capital investment cost battery system

OPEX\(_{PV}\): Operations and maintenance cost PV system

OPEX\(_{BAT}\): Operations and maintenance cost battery system
Appendix C

To find the optimal configuration of the integrated PV-storage system, the module inputs different storage and PV system sizes into the “Self-Consumption Calculation Module”. Based on the calculated self-consumption ratio then the NPV is retrieved from the “Net Present Value Calculation Module” and entered into a matrix that is specific to the scenario. In this manner, a total of 100 matrices (10 matrices per investment year) are constructed. As an example, Figure C.1 shows the matrix that contains the net present value as a function of PV system and storage size for the investment year 2015 under scenario S3 (medium electricity retail and medium electricity wholesale price increases).

![Figure C.1: Net present value as a function of storage and PV system size for electricity price scenario S3 in 2015 (exemplary)](image)

After constructing the matrix for a specific investment year and scenario, a grid search algorithm was used to determine that combination of PV system and storage size which yields the highest overall net present value for the integrated PV-battery system. This value was then compared to the highest NPV achievable without storage to determine the economic value of adding storage to the PV system. In Figure C.1, for example, the highest NPV (5,102 EUR) can be achieved at a PV system size of 4 kWp and a storage size of 4.5 kWh. The highest achievable NPV without storage is 3,674 EUR for a PV system size of 2.4 kWp, leading to an additional NPV due to storage of 1,428 EUR.
Annex II: Curriculum Vitae
CURRICULUM VITAE

Personal Data

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Academic Positions

Since 09/2012 Harvard University, Cambridge, Massachusetts
Research Fellow in the Energy Technology Innovation Policy Group
Since 01/2010 ETH Zurich, Switzerland
Research Associate in the Group for Sustainability and Technology
07/2009 – 09/2009 IMD Lausanne, Switzerland
Visiting Researcher at the Forum for Corporate Sustainability Management

Education

Since 01/2010 ETH Zurich, Switzerland
PhD candidate in the Department of Management, Technology, and Economics
10/2008 – 04/2009 Massachusetts Institute of Technology, Cambridge, Massachusetts
Visiting Student in the Engineering Systems Division (ESD)
09/2006 – 08/2007 University of Waterloo, Ontario, Canada
Visiting Student in the Department of Mechanical Engineering
10/2003 – 06/2009 Braunschweig University of Technology (TU), Germany
Diploma (eq. to MSc) in Mechanical Engineering and Business Administration

Corporate Positions

01/2008 – 03/2008 The Boston Consulting Group, Frankfurt (Main), Germany
Intern in the field of strategic innovation management
Intern in the field of lean management and enterprise transformation
09/2005 – 10/2005 SKF GmbH – Automotive Division, Luechow, Germany
Intern in production planning, production control, supply chain management
05/2003 – 07/2003 Butting GmbH & Co KG, Knesebeck, Germany
Intern in maintenance, testing of materials, construction, cost accounting
Scholarships

Since 05/2011  PhD scholarship granted by the German National Academic Foundation
07/2010 – 08/2010 Scholarship granted by the Swiss National Science Foundation for a summer course at the University of Sussex, United Kingdom
07/2009 – 09/2009 Post-graduate scholarship granted by the German National Academic Foundation for a research stay at IMD Business School, Lausanne, Switzerland
10/2008 – 04/2009 Scholarship granted by the German National Academic Foundation for a research stay at the Massachusetts Institute of Technology, Cambridge, USA
04/2008 – 04/2009 Scholarship granted by the TU Braunschweig for academic achievements
10/2007 – 04/2009 Scholarship granted by the Carl-Friedrich-Gauss Faculty of Economics of the TU Braunschweig
09/2006 - 08/2007 Scholarship granted by the “Dr.-Juergen-Ulderup” Foundation
09/2006 – 07/2007 Scholarship granted by the German Academic Exchange Service for one year of studies at the University of Waterloo, Ontario, Canada
02/2006 – 06/2009 Student scholarship granted by the German National Academic Foundation

Awards & Honors

04/2010  Promotion price of the Faculty of Mechanical Engineering and the German Association of Engineers (VDI) as the best graduate in Mechanical Engineering and Business Administration at Braunschweig University of Technology in 2009
05/2009  MIT Sloan Peer Recognition Award for the organization of the inaugural MIT Sustainability Summit 2009
06/2002  Honor for special performances at school as the best high school graduate granted by the head and the sponsoring association of the Gymnasium Luechow

Skills & Memberships

Language skills:  German (fluent), English (fluent), French (good knowledge), Spanish (basic skills)
Memberships:  Academy of Management (AoM)
             Association of German Engineers (VDI)
             World Wide Fund for Nature (WWF)

Refereeing