THE TWO FACES OF MARKET SUPPORT – HOW DEPLOYMENT POLICIES AFFECT TECHNOLOGICAL EXPLORATION AND EXPLOITATION IN THE SOLAR PHOTOVOLTAIC INDUSTRY

Joern Hoppmann*, Michael Peters, Malte Schneider, Volker H. Hoffmann

ETH Zurich, Department of Management, Technology, and Economics
Weinbergstrasse 56/58, 8092 Zurich, Switzerland
Email: jhoppmann@ethz.ch, Phone: +41-44 632 82 03 Fax: +41-44 632 10 45

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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 (Jaffe et al., 2005; Rennings, 2000). 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 (Dosi and

Marengo, 2007; Nill and Kemp, 2009). 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 (Hendry and Harborne, 2011; Malerba, 2009).

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 (Menanteau, 2000; Sandén, 2005; 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., Jansen et al., 2006; Levinthal and March, 1993) 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., Greve, 2007; He and Wong, 2004). 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]

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).

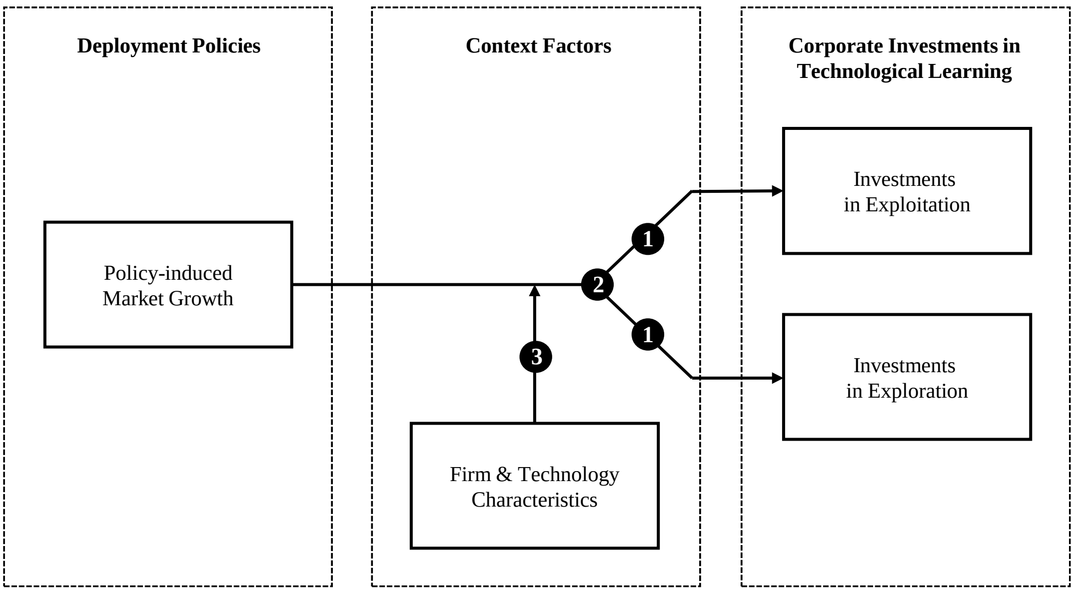

Figure 1: Initial research framework

[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.

3 Research Case

As our research case we chose producers of solar photovoltaic (PV) modules.[2] 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).

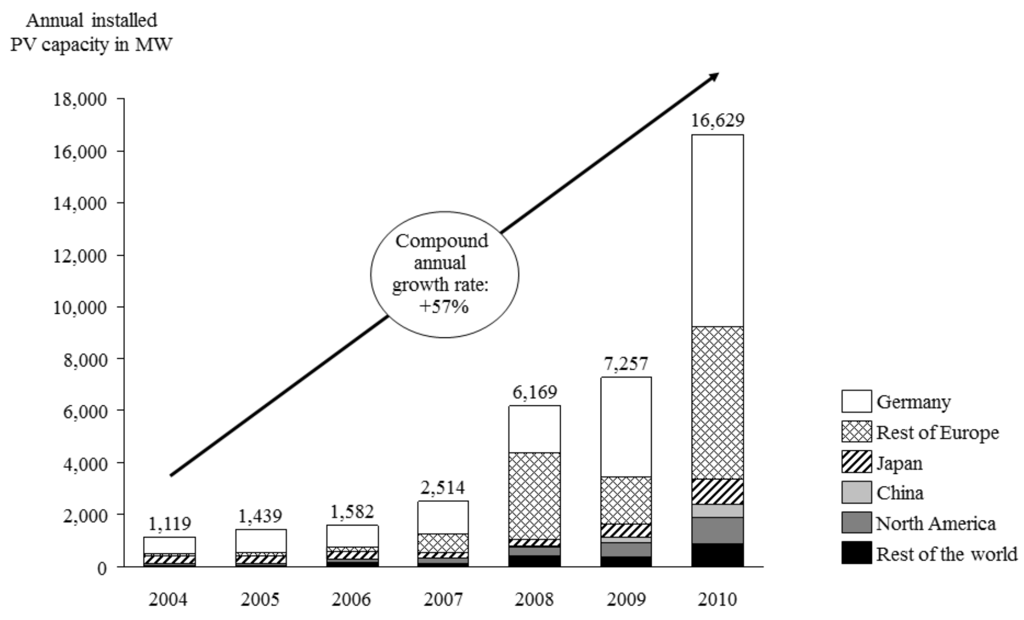

Figure 2: Development of PV markets 2004 to 2010 (data from EPIA, 2011)

[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 (Algieri et al., 2011; Watanabe et al., 2000). 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.

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

Country	**Market Size 2010**	**Market Growth 2010**	**Deployment Policy Scheme 2010**
Germany	7,408 MW	94.6%	Feed-in tariff of up to 0.38 USD/kWh for rooftop, 0.32 USD/kWh for ground-mounted PV
Italy	2,321 MW	223.7%	Feed-in tariff of up to 0.64 USD/kWh for building integrated, 0.53 USD/kWh for ground-mounted PV
Czech Republic	1,490 MW	274.3%	Feed-in tariff of up to 0.64 USD/kWh for rooftop and ground-mounted PV
Japan	900 MW	105.0%	Investment subsidy of 740 USD/kW_p; feed-in tariff for surplus electricity of 0.55 USD/kWh for private households, 0.27 USD/kWh for commercial PV
United States	878 MW	84.1%	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
France	719 MW	228.3%	Feed-in tariff of up to 0.66 USD/kWh for building integrated, 0.53 USD/kWh for ground-mounted PV
China	520 MW	128.1%	Auctioning mechanism and investment subsidies on national level; feed-in tariffs in provinces of Zhejiang, Shandong and Jiangsu
Total (world)	**16,629 MW**	**129.1%**	

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 (Bagnall and Boreland, 2008; Jacobsson et al., 2004). 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).

Table 2: Overview of PV technologies

Category	**Wafer-based Crystalline Silicon**	**Thin Film**	**Emerging Technologies**
Technologies	mc-Si[2], pc-Si[3]	a-Si/µ-Si[4], CIGS[5], CdTe[6]	CPV[7], OPV[8], dye-sensitized
Market Share 2010[1]	86%	13%	< 1%
Technological Maturity	+	○	– [9]
Material Intensity	–	+	+
Conversion Efficiency	+	○	– [10]

[1] Source: Photon (2012)
[2] mc-Si: Mono-crystalline silicon
[3] pc-Si: Poly-crystalline silicon
[4] a-Si/µ-Si: Amorphous/mircromorphous 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 (+)

– Low
○ Medium
+ High

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 sampling[4] 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

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[3] The keywords we searched for were 'R&D', 'research', 'development', 'production', 'manufacturing', 'capacity', 'policy', 'market", 'subsidy', 'feed-in tariff' and 'renewable portfolio standard'.
[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).

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.

Table 3: Overview of expert sample

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

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).

Table 4: Overview of company sample

Category		Firm A	Firm B	Firm C	Firm D	Firm E	Firm F	Firm G	Firm H	Firm I	Sum
Region	Germany	X	X								2
	Rest of Europe			X	X						2
	China					X	X				2
	USA							X	X		2
	Japan									X	1
Technology[1]	Wafer-based crystalline silicon	X		X		X	X			X	5
	Thin-film	X	X			X				X	4
	Emerging technologies				X			X	X		3
Interviewee[2]	General Management/Strategy	3/0	1/1	3/0	1/1	1/1		1/1	1/1		11/5
	Research and Development	2/0		1/1				1/1		1/0	5/2
	Production/Operations	1/1		1/1							2/2
	Policy/Strategic Marketing	2/0				1/0	1/1	1/1		1/1	6/3
	Total	8/1	1/1	5/2	1/1	2/1	1/1	3/3	1/1	2/1	24/12

[1] For a more detailed description of the technology categories see Table 2
[2] Numbers indicate "persons in function interviewed/thereof members of executive board"

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[5]. 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

[5] 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.

Table A.2 in the appendix for a typical interview guide). All interviews typically 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.

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).

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 5: Mechanisms through which policy-induced market growth affects investments in exploration

Mechanism	Exemplary Quote	Source
Positive income effect through exploitation	*"The renewable energy law is important. The profit margin allows us to invest in research."*	Firm A, Chief Operating Officer
	"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."	Firm C, Director Business Development
	"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."	Firm E, President
	"Until the year 2000, PV was a relatively small business [...]. Our PV business unit was very self-contained and not very engaging and outward looking. That all changed in 2000 with the rapid increase in the market. We increased our production facilities. [...] So, the production business has grown significantly. And this has also then led to an increase in the R&D support for PV."	Firm I, Director Research and Development
Increased investor interest	*"Investments in R&D are also a question of financial resources. If there were enough resources available, we could easily employ 15 further researchers in R&D and speed up the process. [...] A bigger market leads to stronger investor interest and a higher availability of capital."*	Firm B, Chief Executive Officer
	"[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&D."	Firm D, Member Board of Directors
	"If there had been no legislation [fostering deployment] in place, investor appetite would not have been there. That was key."	Firm E, President
	"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&D of new technologies."	Firm H, Chief Strategy Officer

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.

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).

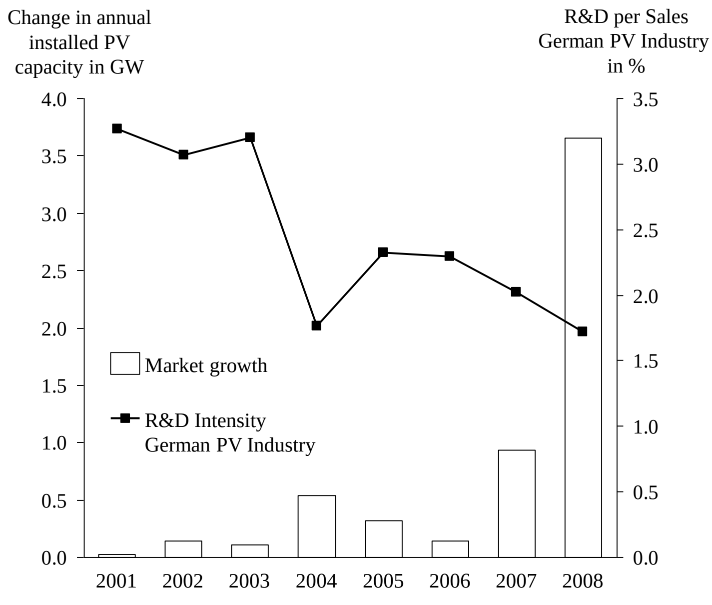

Figure 3: Global market growth and R&D intensity of the German PV industry (data from BSW Solar, 2010; EPIA, 2011, no data available for 2009 and 2010)

During our analysis we found that the phenomenon of declining R&D intensities is not limited to the German PV industry[6] 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 in exploitation by a higher percentage than their investments in exploration for three major reasons.[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 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

[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.

[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.

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). [8] 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.

[8] 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

Mechanism	Exemplary Quote	Source
Reduced exploration pressure	*"There was no need for R&D because the EBIT margin was at an attractive level."*	Firm A, Business Development
	"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."	Firm C, Chief Technology Officer
	"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."	Firm F, Vice President
	"That the firms have not seen R&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&D. If I had a profit margin of 40 or 50 percent and had to make large investments [in R&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."	Project Developer A
Trade-off in use of scarce organizational resources	*"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&D was only second priority."*	Firm A, Strategy Department
	"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&D and worked on building capacities."	Firm C, Chief Operating Officer
	"In the years of high market growth you lose focus on longer-term R&D."	Firm C, Chief Technology Officer
	"If we were a [pure] PV company, you could see that ramping up production would be quite a struggle and R&D might be impacted by that. But we are big enough and have a broad enough portfolio to handle that."	Firm I, Director Research and Development
	"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."	Equipment Manufacturer A
Availability of specialized manufacturing equipment	*"The market growth explains the availability of turn-key equipment."*	Market Analyst/ Consultant A
	"During the Californian Gold Rush 1848, not the gold diggers have become rich but those selling the shovels."	Scientist in Public Research Institute A
	"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."	Firm E, President
	"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."	Firm C, Director Business Development

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 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.*

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

Mechanism	Exemplary Quote	Source
Lack of physically mature product or manufacturing equipment	*"The Renewable Sources Act puts the best available technology on the roof."*	Firm A, Chief Operating Officer
	"In those earlier days you are all about R&D because you are a new company."	Firm B, Chief Executive Officer
	"We are still a pre-commercial company, so every dollar we raise is all going into R&D."	Firm D, Member Board of Directors
	"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."	Firm H, Chief Strategy Officer
	"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]."	Scientist B
Higher barrier to market entry due to lacking economies of scale	*"A few years ago you could build a 20 MW pilot and sell at a reasonable price. Now, 100 MW sounds more reasonable."*	Firm C, Director Business Development
	"Nowadays, it's difficult to enter the market as a player with great R&D since you have to reach 5 GW scale to be competitive."	Firm E, President
	"I think there is still a significant interest in truly innovative early-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."	Firm H, Chief Strategy Officer
	"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."	Firm I, Director Research and Development

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 section 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., Newell et al., 1999; Popp, 2002). 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 economies 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 staggers 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.

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 policy makers 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 policy makers 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.

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Appendix

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

Company name	Country of Origin	Years covered
Arise Technologies Corp.	Canada	2003-2010
Canadian Solar, Inc.	China	2006-2010
China Sunergy	China	2006-2010
Conergy AG	Germany	2006-2010
Day4 Energy, Inc.	Canada	2008-2010
Ersol Solar AG	Germany	2005-2009
Evergreen Solar, Inc.	USA	2000-2009
First Solar, Inc.	USA	2005-2010
JA Solar Holdings, Co. Ltd.	China	2006-2010
Kyocera Corp.	Japan	2004-2009
LDK Solar, Co. Ltd.	China	2007-2010
Q-Cells AG	Germany	2004-2010
Renesola Ltd.	China	2006-2010
Renewable Energy Corporation (REC)	Norway	2003-2010
Sanyo Electric, Co. Ltd.	Japan	1998-2010
Sharp Corporation	Japan	2004-2010
Solar-Fabrik AG	Germany	2005-2009
Solarfun	China	2006-2010
Solargiga	China	2007-2009
Solarworld AG	Germany	2000-2009
Solon AG	Germany	1999-2009
Sunpower Corporation	USA	2007-2010
Suntech Power Holdings, Co. Ltd.	China	2006-2010
Sunways, AG	Germany	2001-2009
Trina Solar Ltd.	China	2006-2010
Yingli Green Energy Holding Co. Ltd.	China	2007-2010

Table A.2: Typical interview guide as used in the case study

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

Table A.3: Evidence for the importance of deployment policies in the PV sector

Exemplary Quote	Source
„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."	Firm A, Policy Department
„Currently, you can substitute the word 'market' with 'policy'. But we want to move beyond this."	Firm A, Chief Operating Officer
"Without policy support, there would be no market […]."	Firm A, Business Development
"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."	Firm C, Director Business Development
"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."	Firm C, Director Business Development
"[T]he 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."	Firm G, Chief Executive Officer
"The market development is driven by policy support."	Firm I, President
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."	Firm I, Director Research and Development
"The feed-in tariffs, especially in Germany, have led to strong growth."	Scientist B
"A market is a necessary condition. For this, we need policy support."	Investor A
"Policy support is very important for the PV industry."	Equipment Manufacturer B
"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 build new plants, the prices didn't come down. Today, with the help of policy, this vicious circle has been broken."	Market Analyst/ Consultant C

Table A.4: Pearson correlations between market growth and firm-level indicators for firms pursuing wafer-based crystalline PV (N=164, t=7)

	Market growth in GW			**Market growth in %**		
	No lag	**Lag = 1**	**Lag = 2**	**No lag**	**Lag = 1**	**Lag = 2**
R&D investments (USD)	0.80*	0.58	0.76*	0.42	0.14	0.51
Increase in production capacity (GW)	0.98**	0.23	0.90**	0.62	-0.18	0.64
R&D intensity (%)	-0.48	-0.55	-0.45	-0.07	-0.50	-0.36

* $p < 0.05$, ** $p < 0.01$

Table A.5: Statements indicating an increasing risk of a technological lock-in in the PV industry

Exemplary Quote	Source
"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."	Firm B, Chief Executive Officer
"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."	Firm C, Director Business Development
"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."	Firm C, Director Business Development
"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."	Firm E, President
"[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."	Firm G, Chief Executive Officer
"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."	Firm I, Director Research and Development
"It is not always the best technology that wins, that is probably true."	Scientist B
"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 for 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."	Market Analyst/ Consultant C
„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."	Market Analyst/ Consultant C
"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."	Policy Maker B