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The Role of Technology Policy in Fostering Technical Change – Lessons from the Cases of Solar and Wind Power

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“We are like tenant farmers chopping down the fence around our house for fuel when we should be using nature's inexhaustible sources of energy – sun, wind and tide. ... I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that.”

– Thomas Alva Edison to Henry Ford in 1931

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Abstract

Climate change has become a very serious threat to mankind and the environment. To limit global warming to a level that prevents major damage the carbon intensity of the global economy has to be slashed by at least an order of magnitude between today and 2050. It is widely accepted that a drastic acceleration of technical change in the field of clean energy technologies is indispensable to reach this goal. In this endeavor the improvement of technology policy will play a crucial role, given that in most settings the diffusion and innovation of clean energy technologies is still strongly dependent on government intervention.

This dissertation aims to derive recommendations for efficient and effective policy support by investigating how technology policy can foster technical change in the field of clean energy technologies. In a first step, the necessity and potential of technical change are analyzed to gain insights into the scope of technology policy required. In a second step, this research scrutinizes causalities between technology policy and innovation – a key building block of technical change. More specifically, in addition to the impact of technology-push and demand-pull policies on innovation, this dissertation examines the innovation effects of foreign vs. domestic policies and challenges the assumption of a time-invariant causal mechanism between demand-pull policies and innovation. Detailed causal mechanisms on a firm-level between technology policy and technological learning are also investigated. Regarding the theoretical background, the dissertation draws on environmental economics as well as evolutionary economic literature. Furthermore, the constructs and antecedents of firm-level learning are reviewed based on the organizational learning literature.

Solar and wind power technologies are used as research cases in this dissertation since hopes are high that they become cornerstones in the battle against climate change. The physical potential of both energy resources is abundant and recent technical change in both fields has been dynamic. In the four individual papers of this dissertation, the data on solar and wind power are combined with a broad set of methods and units of analysis to assure a comprehensive perspective on the phenomenon of technical change. Analyses are conducted across different time horizons as well as on both a country- and firm-level. Techno-economic modeling, econometric analyses based on patent counts and case study research are applied.

Four main contributions emerge from this dissertation. First, it delivers a better understanding of the current and future competitiveness of leading solar technologies across different geographies. It shows that substantial technical change within solar technologies is possible. In order to exploit this potential, however, further policy support will be required until at least 2020. Second, this dissertation provides insights into the geographical dimension of technology policy by indicating that the innovation effect of domestic demand-pull policies does not only accrue within national borders but can also cause substantial spillovers to foreign countries. Third, evidence for the existence of time-variant causal mechanisms between demand-

pull policies and innovation is presented. It is shown that this relationship may be impacted by the life-cycle stage of a technology. Fourth, this dissertation improves the understanding of how demand-pull policies impact technological learning within firms. More precisely, the level of policy-induced market growth is proposed as an important influencing factor of firm-level technological learning. In addition, this relationship seems to depend on the technological maturity of a firm's product.

These contributions are the basis for several policy implications. First of all, policymakers should focus demand-pull policies on the most competitive country-technology combinations to increase the efficiency of policy funding. Excessive policy-induced market growth should also be prevented, since it can trigger 'exploitative' behavior of firms and technological lock-ins. Both would reduce the efficiency of policy funding. This could even hamper technical change as policy investments in specific clean energy technologies may be decreased or abandoned in order to contain costs to society. Furthermore, a supranational demand-pull policy scheme may help to balance the effects of country-level innovation spillovers, which otherwise might lead to insufficient investments in demand-pull policies on a national level. Finally, policymakers should consider technology and country-specific factors when allocating funds to technology-push and demand-pull policies. In addition to policy recommendations also managerial implications are presented. This dissertation concludes with an agenda for further research.

Zusammenfassung

Der Klimawandel ist zu einer sehr ernsthaften Bedrohung für die Menschheit und die Umwelt geworden. Um die globale Erwärmung auf ein Niveau zu begrenzen, das größeren Schaden verhindert, muss die Kohlenstoffintensität der Weltwirtschaft bis 2050 erheblich reduziert werden. Es ist allgemein akzeptiert, dass hierzu eine drastische Beschleunigung des technologischen Wandels im Bereich der sauberen Energietechnologien unabdingbar ist. In diesem Zusammenhang kommt der Verbesserung von Technologiepolitik eine sehr wichtige Bedeutung zu, da die Diffusion und Weiterentwicklung sauberer Energietechnologien noch stark von regulatorischer Unterstützung abhängen.

Das Ziel dieser Dissertation ist es, Empfehlungen für eine effiziente und effektive Regulierung abzuleiten, indem die Bedeutung von Technologiepolitik für technologischen Wandel auf dem Gebiet der sauberen Energietechnologien beleuchtet wird. In einem ersten Schritt analysiert die vorliegende Arbeit den Bedarf an technologischem Wandel und dessen Potenzial, um Einsichten hinsichtlich des Umfangs und der Beschaffenheit der benötigten Technologiepolitik zu erhalten. In einem zweiten Schritt untersucht die Dissertation Kausalitäten zwischen Technologiepolitik und Innovation, einem bedeutenden Element von technologischem Wandel. Insbesondere befasst sich diese Arbeit neben den Auswirkungen von „technology-push“ und „demand-pull“ Politiken auf Innovation mit den Innovationseffekten von inländischen vs. ausländischen Politiken. Weiterhin wird die Annahme eines zeitunabhängigen Kausalzusammenhangs zwischen „demand-pull“ Politiken und Innovation hinterfragt. Zudem untersucht die Arbeit auf Firmenebene wie sich Technologiepolitik auf technologisches Lernen auswirkt. Theoretisch ist diese Arbeit in der Umweltökonomik und der Evolutionsökonomik verankert. Darüber hinaus werden die Konstrukte und Determinanten von technologischem Lernen auf Firmenebene aus der Perspektive der Literatur über Organisationales Lernen beleuchtet.

Solarstrom- und Windkrafttechnologien werden in dieser Dissertation als Fallstudien verwendet, da diese eine elementare Rolle im Kampf gegen den Klimawandel spielen könnten. Das physische Potenzial beider Energiequellen ist mehr als ausreichend und der technologische Wandel auf dem Gebiet beider Technologien war in den vergangen Jahren sehr dynamisch. In den vier Artikeln dieser Dissertation werden die Daten zu Solarstrom- und Windkrafttechnologien mit mehreren Methoden und Analyseeinheiten kombiniert, um eine umfängliche Perspektive auf das Phänomen des technologischen Wandels sicherzustellen. Untersuchungen erfolgen über mehrere Zeithorizonte und auf Länder- wie auch auf Firmenebene. Als Methoden werden technisch-ökonomische Modellierung, ökonometrische Analysen auf Basis von Patentdaten und qualitative Fallstudienfoschung angewendet.

Diese Dissertation leistet vier wichtige Beiträge. Erstens, sie verbessert das Verständnis von heutiger und zukünftiger Wettbewerbsfähigkeit führender Solartechnologien in mehreren Geographien. Sie zeigt, dass substanzieller technologischer Wandel innerhalb von

Solartechnologien möglich ist. Jedoch bedarf es weiterer Politikunterstützung bis mindestens zum Jahr 2020, um dieses Verbesserungspotenzial zu heben. Zweitens, gibt diese Dissertation Einsicht in die geographische Dimension von Technologiepolitik, indem sie zeigt, dass der Innovationseffekt von „demand-pull“ Politiken nicht nur ausschließlich im Inland sondern auch im Ausland auftreten kann. Drittens, präsentiert die Arbeit Anhaltspunkte für einen zeitabhängigen Kausalzusammenhang zwischen „demand-pull“ Politiken und Innovation. Es wird gezeigt, dass dieser Zusammenhang von der Lebenszyklusphase einer Technologie abhängig sein kann. Viertens, trägt die Dissertation zu besseren Kenntnissen über politikinduzierte Mechanismen bei, die zu technologischem Lernen auf Firmenebene führen. Insbesondere wird gezeigt, dass die Höhe des von „demand-pull“ Politiken ausgelösten Marktwachstums technologisches Lernen auf Firmenebene beeinflussen kann. Dieser Zusammenhang scheint zudem davon abzuhängen, welchen technologischen Reifegrad Produkte innerhalb einer Firma haben.

Diese Beiträge sind der Ausgangspunkt für mehrere Politikempfehlungen. Zunächst sollten politische Entscheidungsträger „demand-pull“ Politiken auf die wettbewerbsfähigsten Länder-Technologie Kombinationen fokussieren, um die Effizienz der Förderung zu erhöhen. Weiterhin sollten „demand-pull“ Politiken kein übermäßiges Marktwachstum hervorrufen, da es zu Unterinvestitionen in neue Produkte und zu technologischen „Lock-ins“ führen kann. Beides würde die Effizienz von Politikunterstützung verringern. Dies könnte wiederum technologischen Wandel beeinträchtigen, da öffentliche Investitionen in bestimmte saubere Energietechnologien verringert oder gar aufgegeben werden könnten, um gesellschaftliche Kosten einzudämmen. Darüber hinaus sollten politische Entscheidungsträger auf supranationale „demand-pull“ Politiken hinarbeiten, um die Inkongruenz von Kosten und Innovationseffekten auf Länderebene auszugleichen, welche anderenfalls zu nicht ausreichenden Investitionen in nationale „demand-pull“ Politiken führen könnte. Schließlich sollten politische Entscheidungsträger technologie- und länderspezifische Faktoren bei der Zuteilung von öffentlichen Geldern auf „technology-push“ und „demand-pull“ Politiken berücksichtigen. Neben Politikempfehlungen werden auch Implikationen für Unternehmen abgeleitet. Abschließend zeigt die Dissertation Felder für zukünftige Forschung auf.

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1 Introduction

Climate change is a very serious issue facing society today. Renewable energy technologies (RETs) are widely considered as a crucial lever to address this challenge. Yet in the large majority of markets deployment of RETs still depends on policy support (IPCC, 2011). One of the countries that has acted most determinedly in recent years to diffuse RETs is Germany. The Renewable Energy Sources Act (EEG) enacted at the turn of the millennium propelled the share of renewable electricity generation in Germany from 6% in 2000 to over 20% in 2011 (BMU, 2011a, b). Alone in 2011 the EEG rewarded the feed-in of renewable electricity with an estimated 13.5 billion EUR above market prices (BMU, 2011c). This is equivalent to about 0.5% of Germany's gross national product (GDP). However, in Germany a fierce debate has erupted over whether the benefits of the EEG justify its high cost. In particular, the remuneration for solar power has been criticized, which considerably exceeds market prices and results in significant increases of power prices for end consumers and businesses. In response to these concerns, feed-in tariffs for solar power are currently being cut back. As a result the annual deployment in Germany is expected to decrease substantially (EPIA, 2011). Critics argue that this development runs contrary to the aimed-for 'energy turnaround' in Germany.

Also on a global scale, the level of future policy support for RETs is uncertain. This causes stress for RET companies and lowers investors' faith. While between March 2009, the climax of the financial crisis, and October 2011 the S&P 500 index has gained more than 80%, the RENIXX, a leading stock index for RETs, has lost more than 50%.[1] For RETs to become independent of policy support, their competitiveness has to increase through technical change. However, to induce this technical change, the vast majority of practitioners and academic scholars view policy support in turn as a factor of paramount importance.

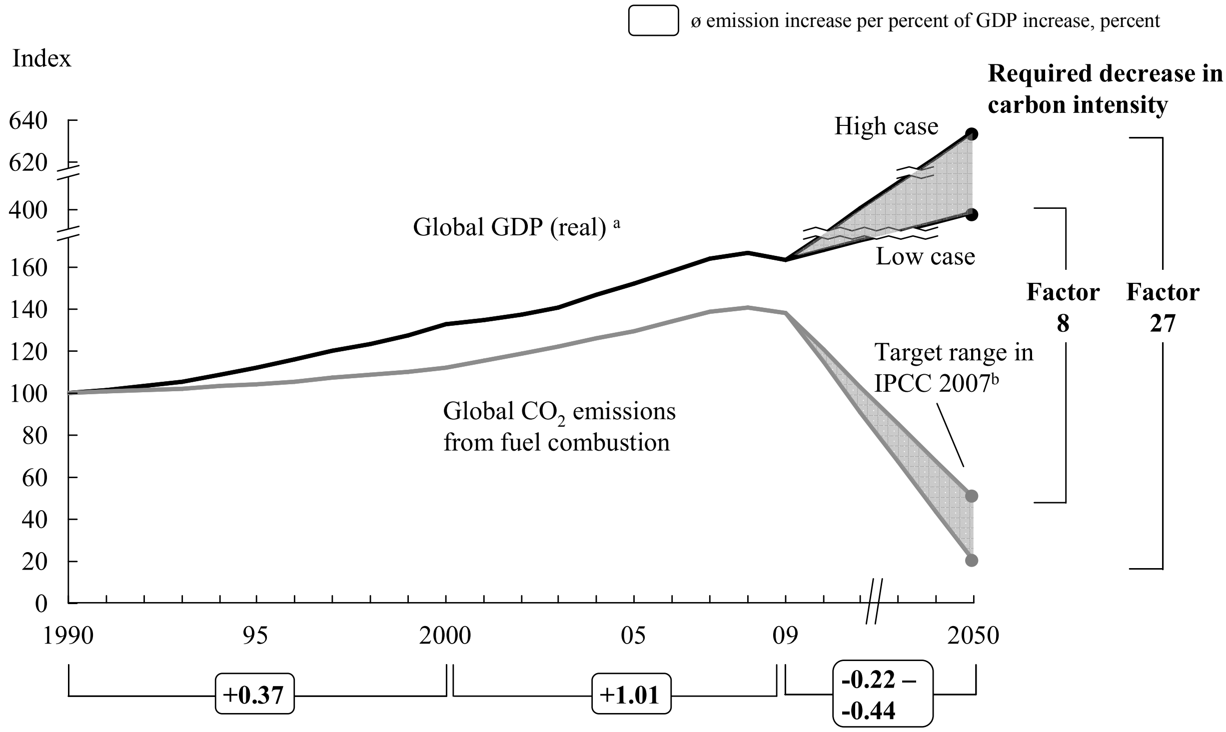
This dissertation investigates how technology policy can foster technical change in order to achieve competitiveness of RETs in most settings. Based on analyses in the fields of solar and wind power, it derives recommendations on how to improve technology policy. In addition, the improved understanding of the relationship between technology policy and technical change is reviewed from a managerial standpoint and recommendations are derived how to successfully navigate firms in policy-driven markets.

1.1 A mammoth task for mankind

There is overwhelming evidence for the existence of man-made climate change (IPCC, 2007b). Scientists have reached the consensus that limiting global warming to 2° Celsius compared to pre-

[1] Differences in index values refer to the period March 5, 2009 – October 21 2011. The S&P 500 comprises the 500 largest publicly listed companies in the US. The RENIXX includes 30 globally leading companies in the field of RETs. As of October 21, 2011, out of 30 companies 15 are active in the solar PV industry and 9 in the wind power industry.

industrial levels is necessary in order to avert serious damage to humans, the environment and the economy (IPCC, 2007c; Stern, 2008). To limit the risk of an overshoot in global mean temperature, a substantive reduction in anthropogenic greenhouse gas (GHG) emissions is imperative. The Intergovernmental Panel on Climate Change (2007a) has derived a target range for GHG emissions reductions of 50-80% until 2050 compared to the level in 1990. Reaching this target requires that increased GHG emissions due to economic and population growth are overcompensated by reductions in carbon intensity, i.e., that GHG emissions growth is decoupled from GDP growth.



a Compound annual growth rate of global GDP 2009 – 2050 in high case 3.4%, in low case 2.2%.
b GHG emissions target applied pro rata to CO_2 emissions from fuel combustion.

Figure 1: Development of global GDP and global CO_2 emissions from fuel combustion; Source: (Galiana and Green, 2009; IEA, 2011; IPCC, 2007b; PricewaterhouseCoopers, 2011; World Bank, 2011)

In the past, governments have taken initial actions to reduce GHG emissions. Foremost under the Kyoto Protocol adopted in 1997, 39 countries committed to a reduction in GHG emissions until 2012 (UNFCCC, 2011). However, these actions were by no means sufficient to achieve a decoupling of emissions from GDP growth. In the past decade CO_2 emissions from fuel combustion that account for more than 80% of global GHG emissions even increased roughly proportionally with GDP. To reach the 2050 emissions target, an improvement in carbon intensity by an order of magnitude or even more is needed between 2009 and 2050 (see Figure 1). To reach the upper (lower) bound of the 2050 emissions target an annual improvement in carbon intensity of 4.5-6.5% (7-8%) would be required – assuming an annual GDP growth of 2.2-3.4% p.a. (Galiana and Green, 2009; PricewaterhouseCoopers, 2011). Even in Europe, the region in the world with one of the most stringent climate regulations, carbon intensity only improved on average by 2% p.a. between 2000 and 2009. Apparently a step change in the rate of decarbonization is essential in the very near future; otherwise society will be confronted with the dangers of climate change. How can we achieve such a step change?

1.2 Need for a technology revolution

Galiana and Green (2009) argue that we need a veritable 'technology revolution' to address the climate change challenge. While other levers such as behavioral change, restricting population and per capita economic growth exist, a massive acceleration of technical change is widely accepted as the silver bullet. The invention, innovation and diffusion (Schumpeter, 1942) of clean technologies can lead the transition to a low- or zero-carbon world.

Key subject of the 'technology revolution' will be clean energy technologies given that the use of energy accounts for more than 80% of global GHG emissions (IEA, 2011).[2] Clean energy technologies either increase the efficiency of energy use or they decrease the emissions per unit of energy produced. The power sector with about 40%[3] of energy-related GHG emissions is by far the highest emitter (IEA, 2011). Yet multiple levers are available in this sector to mitigate GHG emissions. They range from carbon capture and storage, nuclear energy, fuel switching, increases in power generation efficiency to renewable energy technologies (RETs) such as solar and wind power (IEA, 2010b). In many long-term scenarios of the power sector, solar and wind power are assigned a substantial share of the total generation. For example, the International Energy Agency (2010b) estimates solar power to account for 21% and wind for 12% of global electricity generation in 2050 (in sum around 80% of total renewable power generation). Beyond 2050, in particular solar power is believed to have a further upside. Very recently the International Energy Agency argued that solar power may well contribute more than 50% to global power generation in 2060 (Bloomberg, 2011). Hopes are high for solar and wind power technologies for several reasons. First, solar and wind electricity generate a fraction of GHG emissions associated with conventional power generation (IPCC, 2011). Second, the physical potential of both energy sources is several orders of magnitude higher than today's world energy consumption (Nitsch, 2009). For example, a back-of-the-envelope calculation shows that a solar PV power plant covering an area of 450 by 450 kilometers[4] with irradiation conditions of Southern California would be sufficient to match today's global electricity generation. This area corresponds to only 0.1% of the earth's land mass. Third, the majority of energy demand growth will occur in sunbelt countries where conditions for solar power are favorable (Philibert, 2011).

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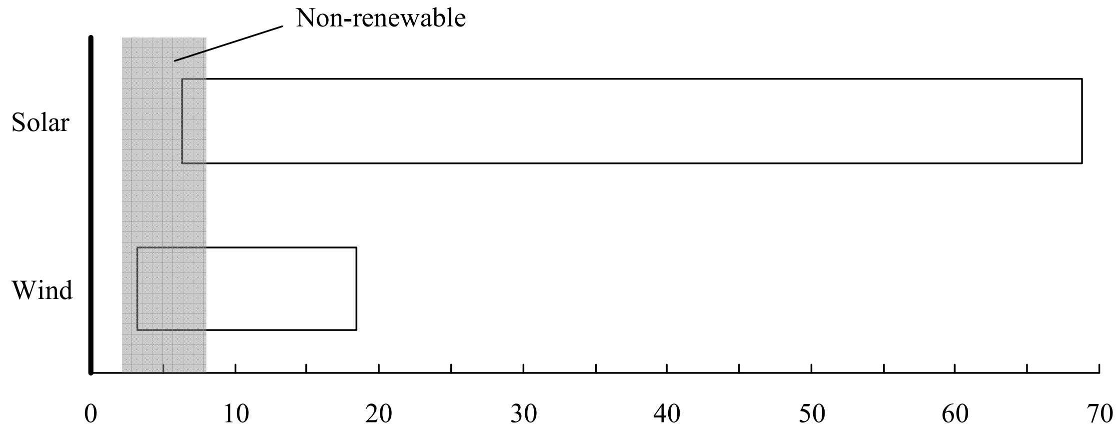
[2] Based on GHG emissions split in Annex I countries of the Kyoto Protocol.
[3] Including central heat generation.
[4] Own calculations; assumptions: 100 kWh/sqm p.a.; world electricity generation in 2008: 20,200 TWh (IEA, 2010a).

Fourth, the dynamics in global solar and wind power markets have been very high in the last decade. Between 2000 and 2010, solar power capacity grew on average at 51% p.a. and wind capacity at 25% p.a.

Levelized cost of electricity[a] (excl. downstream cost[b]) 2011, EUR cents_{2010}/kWh



a Unsubsidized lifetime cost of a power plant per kWh excl. external or internalized environmental cost (e.g, prices for CO_2 certificates); range depends on variations of input-values (e.g., type of technology, capital expenditures per kW installed, discount rate); lower range: most favorable input-values, upper range: least favorable input-values.

b Grid cost; in case of intermittent solar and wind power excl. cost of integration such as storage or required backup capacity.

Figure 2: 2011 competitiveness of solar and wind power; Source: (IPCC, 2011)

However, in most settings, wind, and in particular solar power are not yet competitive with conventional power generation based on, for example, coal or natural gas (see Figure 2). Furthermore, there is a high uncertainty regarding the integration cost of intermittent solar and wind power. The Intergovernmental Panel of Climate Change states that "[t]he available literature on integration costs is sparse and estimates are often lacking or vary widely." (IPCC, 2011 p. 15) Therefore, solar and wind power depend almost exclusively on policy support. Their current (2010) share in global electricity generation is still marginal with less than 0.5% and 2% respectively. To exploit the enormous physical potential of both energy sources, additional policy support is critical to foster technical change, which could ultimately allow these technologies to reach 'sustainable markets'.

1.3 Need for smart technology policy

In the case of clean technologies, the large majority of practitioners and academic scholars have come to the conclusion that technology policy is indispensable to foster technical change (e.g., Del Rio Gonzalez, 2009). The two principal types of technology policy are technology-push policies, such as public R&D funding, or demand-pull policies (also referred to as deployment policies) that create markets, for example, through feed-in tariffs or investment subsidies (Rennings, 2000). Both technology-push and demand-pull policies can incentivize R&D activity, which should result in invention and innovation. In addition, demand-pull policies enable the diffusion of clean technologies, which should then lead to innovation through experience gained in production, field tests and long-term use.

While empirical evidence backs the ‘innovation inducement’ effect of technology-push and demand-pull policies (e.g., Taylor et al., 2005), it is much less clear how to apply a ‘smart’ – i.e., efficient and effective – technology policy mix that fosters urgently needed technical change. An example of this lack of clarity is the debate around current policy schemes for solar power, which reflects the disaccord regarding three attributes of such policies: cost, technological focus and geography. While some industry participants and pundits argue that PV will become competitive in the very near future (e.g., Asbeck, 2009), others highlight the long-term future cost to society resulting from policy support from PV (e.g., Frondel et al., 2008). There are also differences regarding the implicit or explicit technological focus induced by policy schemes. For example, the feed-in tariff for concentrating solar power plants in Spain seems to rather incentivize the use of more mature technology, whereas in the US in the same domain more diverse technological approaches can be found (Emerging Energy Research, 2010). The geography aspect of policy is highlighted by the example of Germany, the leading solar PV market in the world (45% market share in 2010). On the one hand, it’s argued that the national benefits of decentral power generation in Germany based on solar PV such as local value creation are worth the costs (juwi, 2011). On the other hand, import of solar power from regions with substantially higher insolation than Germany are considered to be more efficient (DESERTEC Foundation, 2011).

A better understanding of the relationship between technology policy and technical change would be highly beneficial to derive recommendations for a smart technology policy. This dissertation therefore scrutinizes the role of technology policy in fostering technical change. The following Section outlines the overall objective of the dissertation. After a presentation of the methods (Section 3), all four papers that are part of this dissertation are summarized in Section 4. The conclusion (Section 5) highlights the dissertation’s contributions, presents policy recommendations and outlines a future research agenda. Section 6 provides an overview of all individual papers (see Annex I for the full text of the papers).

2 Objectives

The imperative of designing smart technology policy in order to tackle the issue of climate change has been outlined in the preceding Section. Therefore this dissertation's objective is to derive recommendations for more efficient and effective technology policy by addressing the following question:

How can technology policy foster technical change in the field of clean energy technologies?

In order to answer to this question, this dissertation investigates important gaps in the extant literature on the link between technology policy and technical change by scrutinizing the cases of solar and wind power. In a first step, the dissertation assesses the necessity and potential of technical change with the objective to gain insights into the current and future scope and quality of technology policy required to accelerate technical change (paper I). In a second step, this research intends to improve the understanding of the causalities between technology policy and technical change. In doing so, a focus lies on innovation as a key building block of technical change. More specifically, in addition to the impact of technology-push and demand-pull policies on innovation, the role of foreign vs. domestic policy locus is to be examined on a country-level (paper II). A similar analysis, yet considering the influence of the technology life-cycle stage, has the objective to challenge the assumption of a time-invariant causal mechanism at work between demand-pull policies and innovation (paper III). Then this dissertation chooses a micro-level perspective to also better understand detailed causal mechanisms between demand-pull policies and technological learning within firms (paper IV). The overall framework underlying this dissertation is depicted in Figure 2. More detail on the objective and specific research gap addressed in each individual paper is provided below.

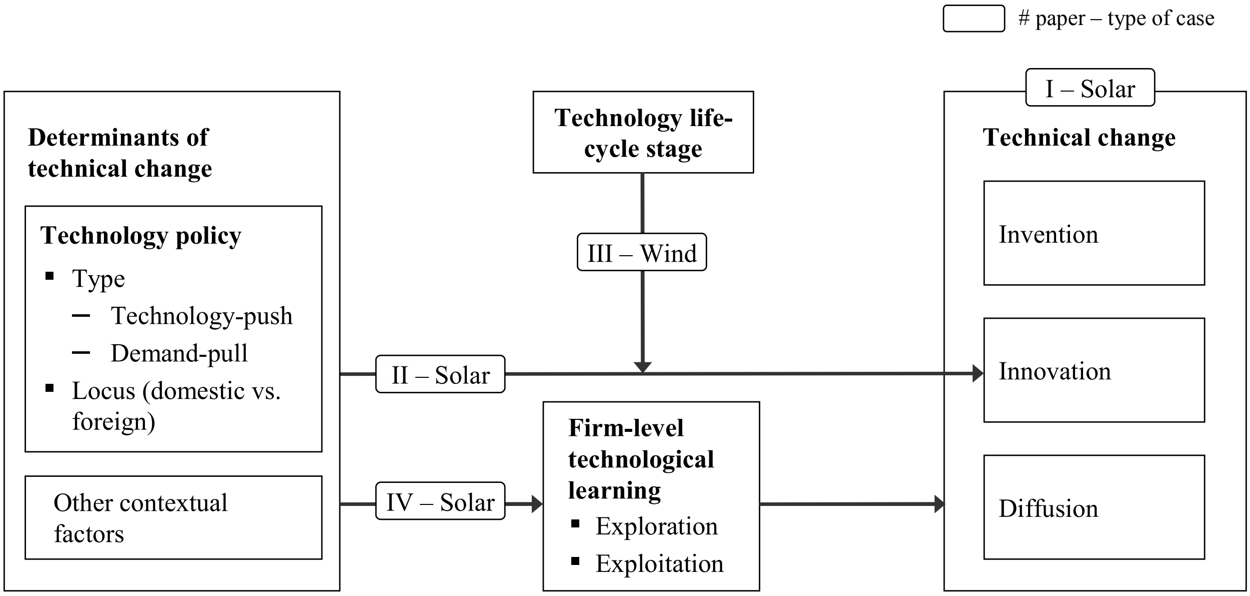


Figure 2: Framework of the dissertation

Paper I examines the *necessity* and the *potential* of technical change in the field of solar technologies by assessing their competitiveness in different countries across 4 continents in 2010 and 2020. In contrast to papers II – IV, which aim to derive recommendations for future policymaking based on past cause-effect relationships, the primary objective of this study is to better understand the future competitiveness of different country-technology combinations. This analysis is then to inform policymakers about a) the need for future technology policies and b) which technologies in which countries should receive support. Thus far the literature has fallen short of providing a holistic assessment of solar power that considers the three key dimensions influencing the competitiveness of solar electricity generation: technology, time and location.

Paper II analyzes the impact of technology policy on innovation for the case of solar PV across 15 OECD countries in the period 1978 to 2005. The objective of this paper is to scrutinize the impact of domestic and foreign technology-push and demand-pull policies on innovation. This analysis allows policymakers to better understand to what extent the benefits of domestic policy funding accrue to foreign countries and to devise strategies that address the potential issue of such country-level innovation spillovers. While the extant literature has come to the conclusion that technology-push as well as demand-pull policies induce innovation, these studies have primarily focused on domestic technology policy. The limited number of studies analyzing the innovation effect of foreign policies yields inconclusive results.

In addition to the factors scrutinized in paper II, paper III examines the role of technological diversity. Using the technology life-cycle stage as a proxy for diversity, it addresses the question of how a technology's life-cycle stage moderates the impact of demand-pull policies on innovation. Wind power technology is chosen as a research case since, as opposed to solar power technology, it has passed through all major life-cycle stages and converged to a dominant technological paradigm. The analysis is to provide policy advice tailored to specific life-cycle stages. Extant empirical studies have not yet assessed the potentially moderating role of the technology life-cycle stage.

In contrast to papers II /III and previous studies, paper IV focuses on the detailed firm-level mechanisms through which demand-pull policies[5] impact innovation. Its objective is to examine how demand-pull policies incentivize firms to ‘explore’ new products through R&D activities and to ‘exploit’ existing products through the expansion of production. The results are meant to inform policymakers on how to improve the design of demand-pull policies in case such policies induce suboptimal levels of exploitation and exploration.

In conclusion, the individual papers (see Table 1) as well as the dissertation as a whole aim to advance the understanding of the relationship between technology policy and technical change in order to gather insights for smarter technology policy. While a primary focus of this research is policy recommendations, a secondary objective is to review the results from a corporate standpoint and to derive managerial implications. In addition, new insights into the causal mechanisms between technology policy and technical change should offer fruitful implications for theory building. Finally, this dissertation aims to present an agenda for future research.

Table 1: Research questions of papers included in this dissertation

	Title	**Research question**
I	Shedding light on solar technologies – a techno-economic assessment and its policy implications	What is the competitiveness of leading solar technologies depending on time and location?
II	The impact of technology-push and demand-pull policies on technical change - does the locus of policies matter?	How do the innovation effects of domestic and foreign demand-pull and technology-push policies differ?
III	The effect of demand-pull policies on innovation in different technology life-cycle stages – the case of wind power	How do demand-pull policies impact innovation in different phases of the technology life-cycle?
IV	The two faces of market support – how deployment policies affect technological exploration and exploitation in the solar photovoltaic industry	Through which causal mechanisms do deployment policies affect corporate investments in technological exploration and exploitation?

[5] Referred to as deployment policies in paper IV.

3 Theoretical background

This dissertation uses environmental economics, evolutionary economics and draws on the organizational learning literature to improve the understanding of the relationship between technology policy and technical change. A brief overview of this dissertation's theoretical background is provided below. In Section 3.1, the theory of technical change is reviewed. The relevance of technology policy for technical change is then shown from an environmental economics and an evolutionary economics perspective (Section 3.2). Finally, Section 3.3 presents an overview of the literature on exploration and exploitation, which is applied in this dissertation to analyze how firm-level learning is impacted by technology policy.

3.1 Theory of technical change

Already in the 18th and 19th century economists recognized the crucial role of technical change for creating economic growth (e.g., Marx, 1847; Smith, 1776). However, it was only after World War II that scholars presented the empirical evidence for this relationship (e.g., Solow, 1956). In the 1950s and 1960s, two kinds of theories emerged explaining technical change: 'technology-push' and 'demand-pull' (Dosi, 1982). The technology-push concept assumes a supply-side-driven mainly linear process from research to development and ultimately to diffusion and received two principal critiques: First, the underlying linear model of innovation refrained from any iterations and feedback loops, which were later found to be a key element of the innovation process (Kline, 1986). Second, it was considered to be "economically naïve" (Rosenberg, 1994, p. 139), for example, it did not take any prices into consideration. In response to the advocates of the technology-push concept, Schmookler (1966) formulated the demand-pull hypothesis postulating that anticipated market demand was a key determinant of technical change by incentivizing research in new directions. Three main arguments were cited against the work of Schmookler: the concept was said to be broad and difficult to define (Mowery and Rosenberg, 1979; Myers and Marquis, 1969), empirical tests yielded a weak role of demand in explaining technical change (Kleinknecht and Verspagen, 1990; Scherer, 1982), and it was argued that innovators have only limited capabilities to identify and satisfy latent demands (Simon, 1959). Building on these arguments, the debate has reached a consensus that a combination of both factors is necessary to explain technical change, as they closely interact (Mowery and Rosenberg, 1979) and are believed to be complementary in their effects. For example, Freeman (1974) and Arthur (2007) point to synergistic effects created by an interaction of both factors.

The above conception of demand-pull and technology-push factors determining technical change falls short of considering the heterogeneous behaviour of firms. This working within the so called 'black box', however, is a crucial determinant of technical change (e.g., Schumpeter, 1934). Much based on Schumpeterian thinking and drawing on Darwin's (1859) evolutionary principles of variation and selection, an evolutionary perspective on technical change emerged. In this stream of literature, firms are viewed as 'boundedly rational' given their substantial cognitive limitations (Nelson and Winter, 1982). They use 'organizational routines' (Cohen et al., 1996) to cope with the environmental complexity and selective pressures. These routines are highly firm-specific given the tacitness of knowledge and the self-reinforcing nature of many learning mechanisms (Dosi, 2007). Over time, routines ('genes' of an organization) mutate and create diversity, which is then exposed to market-based selection pressures. Evolutionary economists suggest that this process triggers technical change.

3.2 Technology policy and technical change

It is broadly accepted that technology policy is a prerequisite for inducing technical change amongst most clean energy technologies (e.g., Del Rio Gonzalez, 2009). Within the environmental economics literature, this is reasoned with the 'double externality problem': First, negative external effects inherent in most environmental issues put the relative competitiveness of environmental technologies at a disadvantage and, second, as most clean energy technologies still require substantial R&D investments to reach competitiveness, they suffer especially from knowledge spillovers (Rennings, 2000; Weiss and Bonvillian, 2009). To resolve these 'market failures' environmental economists suggest technology policy as a means to foster technical change (Horbach, 2008). Drawing on the theory of technical change, scholars have used the dichotomy of technology-push and demand-pull to scrutinize the impact of policy on technical change (Rennings, 2000). While the focus of most environmental economics studies is on different policy instruments such as tradable permits or feed-in tariffs (Jaffe et al., 2002; Jänicke and Lindemann, 2010), there is a consensus that a positive 'innovation inducement' effect of both technology-push and demand-pull policies exists (e.g., Newell et al., 1999; Watanabe et al., 2000).

In addition, scholars of evolutionary economics have devised approaches to technology policy. In contrast to environmental economics, they do not assume policy to correct for externalities in an otherwise efficient market (Metcalfe, 1994; 1995; Nill and Kemp, 2009). It is rather argued that technology policy can foster technological learning and help to prevent or break technological lock-ins that can occur due to factors such as increasing returns to scale or network externalities (Malerba, 2009). In particular, demand-pull policies may be well suited to trigger technical change as they create niche markets for clean energy technologies shielded from competition with established technological regimes (Kemp et al., 1998).

3.3 Organizational learning literature: exploration and exploitation

March (1991, p. 71) suggests that firms choose between two basic modes of learning: i) 'exploration', which he defines as "search, variation, risk-taking, experimentation, play, flexibility, discovery, and innovation", and ii) 'exploitation', which includes terms like "refinement, choice, production, efficiency, selection, implementation and execution”. While he argues that firms have to apply both types of learning to survive in the long-term, he points out that exploration and exploitation constitute a trade-off as they compete for scarce organizational resources.

Since March’s seminal article, many scholars have investigated the interplay between exploration and exploitation on different levels of analysis ranging from the individual to the industry-level. Early studies narrowly applied March’s framework to scrutinize the trade-off between knowledge generation and utilization within firms. The scope of exploration/exploitation studies then widened to include contexts as diverse as technological innovation and strategic alliances (Lavie et al., 2010). One of the most debated aspects of March’s framework is his statement that “maintaining an appropriate balance between exploration and exploitation is a primary factor in system survival and prosperity” (March, 1991, p. 71). Whereas some studies found that ‘ambidexterity’, i.e., a simultaneous pursuit of exploration and exploitation, led to superior performance of firms (Tushman and O'Reilly, 1996), others provided empirical evidence that firms focussing on one of the two types of learning may outperform their competitors (Ebben and Johnson, 2005). In recent years, this ambiguity has led to a search for antecedents influencing the balance between exploration and exploitation.

Scholars argue that the exploration/exploitation balance chosen by organizations depends on industry-level antecedents such as environmental dynamism (Jansen et al., 2006; Kim and Rhee, 2009) or competitive intensity (Jansen et al., 2006; Levinthal and March, 1993) and firm-internal factors such as a firm’s slack resources (Cyert and March, 1992; Greve, 2007; Nohria and Gulati, 1996). However, thus far there are no empirical studies that investigate a potential impact of public policy on the exploration/exploitation balance (Lavie et al., 2010).

4 Methods

To gain insights into complex issues such as the relationship between technology policy and technical change it is beneficial to conduct analyses from multiple perspectives. Regarding scientific methods, Del Rio Gonzalez (2009) points out that given the complementarity of quantitative and qualitative methods a combination of both is fruitful. While quantitative methods are typically top-down and aggregate, qualitative approaches such as case studies enable more granular analyses on the actor level. For example, Taylor and colleagues (2005) show that for the case of SO_2 regulation the use of both quantitative and qualitative methods yields better results than does an analysis based on a single method.

Table 2: Overview of methods and research cases used in the individual papers

	Title	Method	Research case
I	Shedding light on solar technologies – a techno-economic assessment and its policy implications	Quantitative and qualitative • Techno-economic assessment	Solar power (photovoltaics, concentrating solar thermal)
II	The impact of technology-push and demand-pull policies on technical change - does the locus of policies matter?	Quantitative • Patent analysis • Econometric panel analysis	Solar power (photovoltaics)
III	The effect of demand-pull policies on innovation in different technology life-cycle stages – the case of wind power	Quantitative • Patent analysis • Econometric panel analysis	Wind power
IV	The two faces of market support – how deployment policies affect technological exploration and exploitation in the solar photovoltaic industry	Qualitative • Case study research	Solar power (photovoltaics)

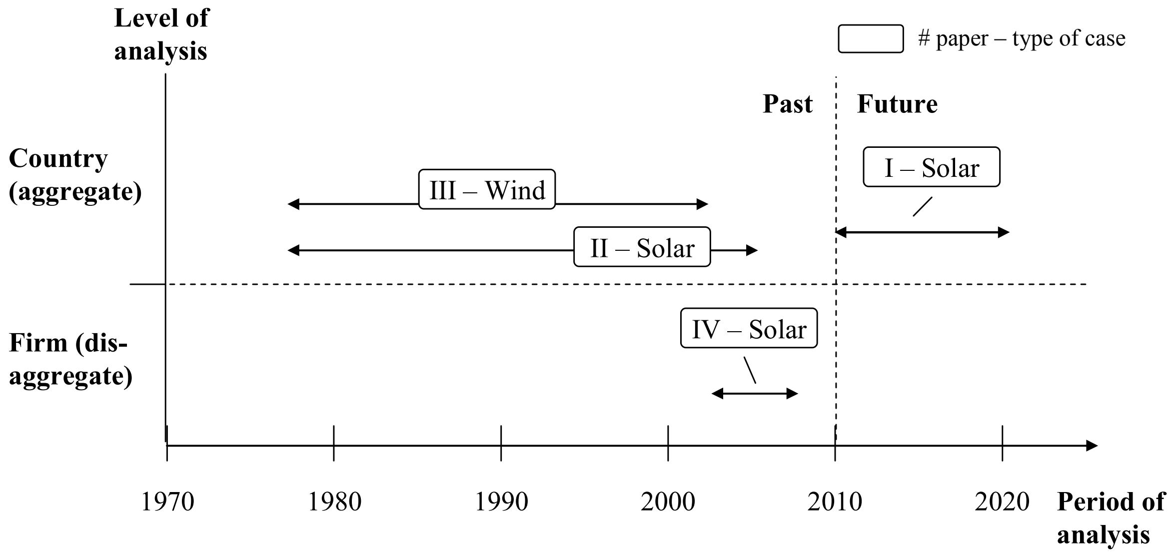


Figure 3: Individual papers' level and period of analysis

Therefore to better understand the relationship between technology policy and technical change, this dissertation is founded on multiple quantitative and qualitative methods applied to the cases of solar and wind power (see Table 2). In addition, to assure a comprehensive perspective on the phenomenon of technical change, the analyses in this dissertation span aggregate (country) and disaggregate (firm) levels of analysis as well as different time periods (see Figure 3). Below we provide details on the methodologies applied in papers I-IV.

4.1 Techno-economic assessment

Paper I applies a quantitative and qualitative techno-economic assessment to analyze the current and future competitiveness of the leading large-scale solar technologies in five locations across four different continents.

Regarding the quantitative assessment, generation and storage costs of solar technologies are scrutinized in a levelized cost of electricity (LCOE) model. The LCOE is the life-cycle cost of a power plant relative to its life-cycle electricity generation. It is the gold standard in comparing the cost of different power generation technologies since it reflects technology specificities such as plant lifetime, investment and output per unit of capacity installed. The following LCOE formula was used (see also Kost and Schlegl, 2010):

$$\frac{\sum_{n=0}^{N} \frac{CAPEX + OPEX}{(1+i)^n}}{\sum_{n=0}^{N} \frac{kWh_{initial,\,net} \times (1 - Degrade)^n}{(1+i)^n}}$$

where CAPEX and OPEX are cash outflows. The net electricity production is determined by the initial production ($kWh_{initial, net}$) and the degradation factor (Degrade). i is the discount rate and n the plant lifetime. All data used in the LOCE calculations stem from secondary sources. Determinant values for 2020 were –wherever possible – estimated bottom-up (Neij, 2008) instead of using learning curves that yield cost estimates with a rather high uncertainty band (Nemet, 2006).

Regarding the qualitative assessment, in a first step seven additional merit dimensions (e.g., technological uncertainty, resource bottlenecks) were compiled based on an extensive literature review and interviews with three leading solar industry experts. The relevance for current and future competitiveness of solar technologies served as the selection criterion. In a second step, each solar technology was assessed along the seven merit dimensions, again using data from archival and expert interview sources.

4.2 Patent analysis

Paper II and III use patent counts to measure innovation in 15 OECD countries in the periods 1978 to 2005 and 1978 to 2002, respectively. In Section 4.2.1 benefits and limitations of patent counts as a measure of innovation will be presented. Section 4.2.2 addresses the issue of highly skewed patent values. After providing insights into the definition of the search filter (4.2.3), Section 4.2.4 outlines how truncation biases in patent data were avoided.

4.2.1 Measuring innovation with patent counts – benefits and limitations

Patent counts are widely accepted as a measure of innovation (Griliches, 1990a; Jaffe, 1986; Schmookler, 1966). Since patent data provide detailed information on inventive activity and are broadly available across time and countries at very low cost (OECD, 2009), its use has been very popular among researchers in the field of innovation studies. However, patent data should be handled with great care as they have some clear limitations of which the most important are outlined in the following (see Griliches, 1990b for a more comprehensive overview of limitations): Above all, not all innovations are patented (Hall et al., 2005). Yet, it is reasonable to assume that patented inventions are a good proxy for all inventions (Schmoch, 1997). In addition, different patenting behavior across patent offices and over time – if not controlled for – can impair the comparability of patent data (OECD, 2009). Furthermore, the value of patents is highly skewed (e.g., Harhoff et al., 2003). Trajtenberg (1990) notes that simple patent counts do not necessarily reflect innovative output. Hence patent value criteria are required to assure that patent counts measure not only invention but also innovation (Hall et al., 2001) (see 4.2.2). Finally, given the heterogeneity of patent data, assigning patents to any type of classification is challenging (Griliches, 1990b). To generate a robust patent data set, a rigorous search filter is of utmost importance (see 4.2.3). Despite these limitations, a statement by Schmookler (1966, p. 56) still holds true: "We have a choice of using patent statistics cautiously and learning what we can from them, or not using them and learning nothing about what they alone can teach us."

In paper II and III the patent application date (instead of the publication date) and the resident country of the inventor are used to measure the date and location of an invention (OECD, 2009). Patent families instead of singular patents (publications) were counted since one patent family typically represents one invention.

4.2.2 Addressing the skewed nature of patent values

While a few patents are highly valuable, most patents hardly represent innovations since their commercial value is very limited. For this reason scholars use a variety of value criteria to assure the measurement of innovation (see Harhoff et al., 2003 for an overview). In paper II the patent family size[6] serves as a value criterion. More specifically, 'claimed priorities' – patent families with publications in at least two countries – and 'triadic patents'[7] approximate innovation (Frietsch and Schmoch, 2010; Sternitzke, 2009). Paper III uses the number of forward citations (citations received from subsequent filings) to establish a value threshold. Patents that received at least one forward citation within five years after application ('citation window') were included in the data set. A 'citation window' is required to give each patent an equal chance of being cited. According to mutiple scholars (Albert et al., 1991; Harhoff et al., 2003; Pavitt, 1988) both criteria family size and forward citations are very well suited to assess the value of a patent.

4.2.3 Defining a search filter

To compile a patent data set with a certain technological scope, a search filter is required. Patent classifications such as IPCs (international patent classifications), key words or a combination of both are used to generate a patent sample. In paper II relevant IPCs for solar PV technology were selected based on a literature research (e.g., Johnstone et al., 2009) and advice from experienced patent researchers. The search filter in paper III combines a key word search with the IPC 'wind motors' to detect patents related to wind power technology. Keywords were selected with the help of industry experts and the literature (e.g., Margolis and Kammen, 1999). Both search filters were designed in an iterative process: Based on random samples the relevance of the patent data was tested multiple times and each time the search filters were adapted accordingly to reduce errors of inclusion. The construction of a search filter is always a trade-off between errors of exclusion and inclusion. For the purpose of the research in this dissertation, inclusion errors were considered to be more severe as they may significantly bias the data set (Dechezleprêtre et al., 2008). However, exclusion errors are acceptable – at least to a certain extent – since a significant share of patents in a technological field are typically a good proxy for the entire PV patent universe in this field (Dechezleprêtre et al., 2008). Paper II ultimately refrained from using key words in the search filter as this strategy significantly increased errors of inclusion. The reason was that solar PV

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[6] Numbers of publications per family.

[7] Patent families with publications in at least Germany or the European Patent Office, Japan or China, and the US.

technologies are very closely related to other technological fields such as image sensors. In contrast, for technological fields with highly characteristic technological components like wind power (paper III), key word searches are well-suited.

While inclusion errors were estimated based on relevance tests of random samples, in paper III the magnitude of exclusion errors could also be assessed. This was done by measuring the share of the patents filed by the ten largest turbine manufacturers, which the search string did not detect. Such an analysis was not possible in case of solar PV (paper II) since during the time of observation manufacturers of solar PV were mainly not ‘pure players’.

All patent data used in this dissertation were extracted from the International patent Family Database (INPAFAMDB) of The Scientific & Technical Information Network (STN). The database covers the full spectrum of patent technologies for 95 issuing authorities, dating from the early 1800s.

4.2.4 Addressing truncation biases

A potential bias within patent data is caused by truncation. Recent patent counts are not comparable with earlier counts since patent information enters databases with a time lag. First, about 18 months pass until all patent applications are published in databases. When value criteria such as patent family size (paper II) or forward citations (paper III) are used, additional time lags occur. After publication it can take patents some years to become a ‘claimed’ or a ‘triadic’ patent. Second, in the case of forward citations, only citations that are received within a certain time period after application (‘citation window’) are counted to ensure that all patents have equal opportunities to be cited. However, recent patents could still suffer from truncation since they may have not outlived a full ‘citation window’ yet. In papers II and III sufficient time lags were included to assure that truncation of patent data was not an issue.

4.3 Econometric panel analysis

An econometric panel analysis scrutinizes variations in innovation depending on changes in explanatory variables. It is therefore well-suited to investigate the impact of technology policy on innovation. Papers II and III construct panel data across 15 OECD countries in the periods 1978 to 2005 and 1978 to 2002, respectively. Patent counts approximate innovation (dependent variable), while for example public R&D funding is used as a measure for technology policy (independent variable).

Common methods to regress count data variables such as patents are the Poisson model and the negative binomial model (Hausman et al., 1984). Given the over-dispersion of patent data used in paper II and III, the negative binomial model was preferred over the Poisson model in both papers. Due to the high amount of zero counts in the wind power patent set (paper III), a zero-inflated negative binomial model was used as a standard specification. All models include country-fixed effects to capture country-level heterogeneity (e.g., differences in patenting standards). Also, other scholars widely use the negative binomial fixed effects model to conduct econometric panel analyses based on patent counts (e.g., Brunnermeier and Cohen, 2003).

In order to correct for autocorrelation and heteroskedasticity present in the solar PV (paper II) and wind power (paper III) data sets, heteroskedasticity- and autocorrelation-consistent (HAC) standard errors are reported. To prevent multicollinearity in the regression models, variance inflation factors and bivariate Pearson correlation coefficients were considered when selecting independent variables. Since the dependent variable 'patent counts' and the independent variable 'public R&D funding' potentially simultaneously cause each other, a test for endogeneity was conducted in paper II. However, no proof for endogeneity was found. Overall, model fitness was assessed using the Akaike Information Criterion, the deltas between actual and fitted means, Tukey-Anscombe plots and quantile (Q-Q) plots.

4.4 Qualitative case study research

Paper IV applies qualitative case study research (Eisenhardt, 1989; Yin, 2009) to investigate the relationship between demand-pull policies and firm-level investments in technological exploration and exploitation. According to Eisenhardt (1989), the case study analysis allows researchers to detect causal mechanisms, and thereby contributes to theory building. Furthermore, a phenomenon can be scrutinized in greater detail by using case study research instead of quantitative methods.

The analysis in paper IV comprises three steps. First, to gain a better understanding of the constructs in the research framework, comprehensive desk research was conducted. Second, 16 leading industry experts with diverse backgrounds (Eisenhardt, 1989; Yin, 2009) were interviewed to further develop insights regarding causal relationships between constructs. Third, based on discussions with 24 managers from 9 companies manufacturing PV modules the understanding of causal mechanisms at work was deepened. Theoretical sampling was applied to select companies. This included the assurance of heterogeneity along the following criteria to account for the potential influence of firm-internal and market factors: type and maturity stage of PV technologies, location of company, and size of company. As interviewees, company representatives with the supposedly best knowledge about the constructs and causal mechanisms were selected, i.e., members of the top management board as well as managers in the R&D, the production and the strategic marketing departments.

To increase the internal validity of the framework during the third research phase, additional expert interviews were conducted and whenever possible at least two representatives per company were interviewed (Eisenhardt and Graebner, 2007). All documentation (recorded or handwritten notes) from the semi-structured interviews that were conducted by at least two researchers was consolidated in a central case study database. Analytical induction was applied to deduce theoretical insights (Manning, 1982). After each interview, researchers independently reviewed interview transcripts and then used pattern matching to find interview quotes that describe causal mechanisms between the constructs in the research framework (Yin, 2009). Subsequently, the research framework was updated by refining constructs and deriving propositions. This iterative process ensured a high level of internal and construct validity of the research framework (Gibbert et al., 2008). Interviews with company representatives and experts were added until additional theoretical insights became minor.

5 Summary of the papers

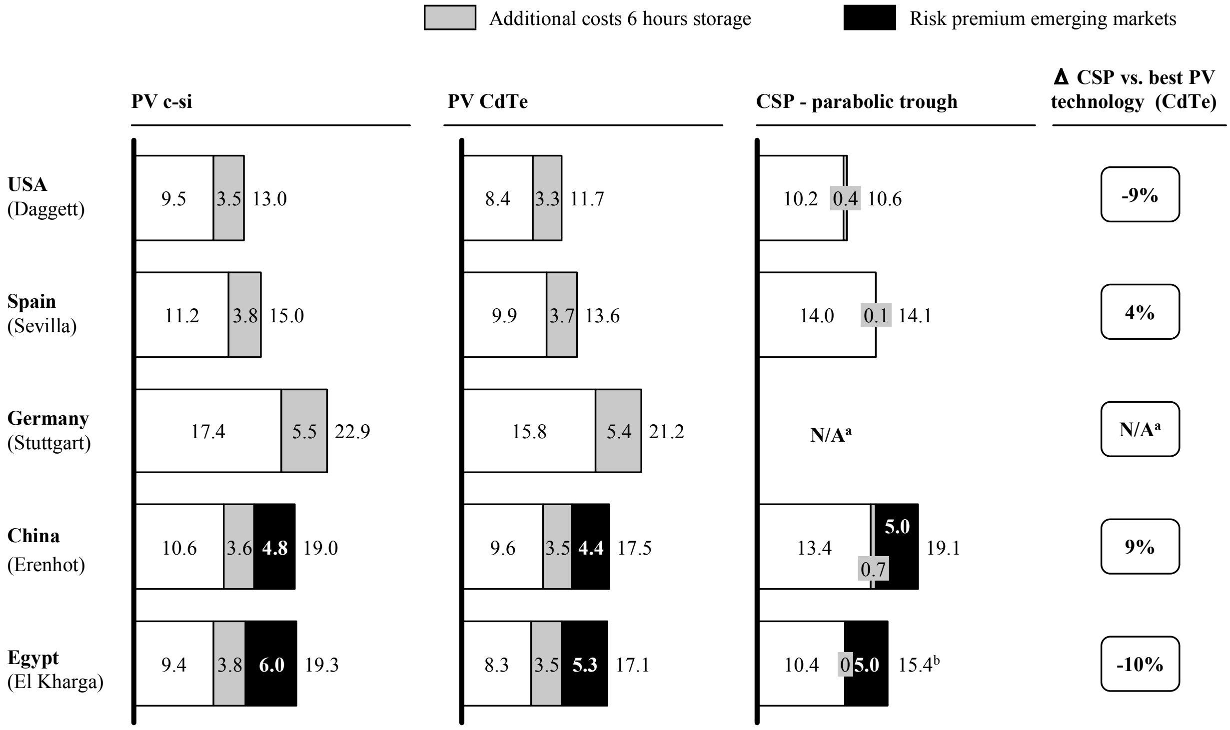
5.1 Shedding light on solar technologies – a techno-economic assessment and its policy implications

Owing to the abundance of solar energy on earth, solar power technologies have the potential to play a crucial role in the world's future energy system. Yet as of today the contribution of solar power to global electricity generation is miniscule since the cost of solar electricity is well above market prices. While currently various solar technologies are competing to reach the benchmark of fossil fuel-based electricity generation sometime in the future, the most viable technology now and in the future is the subject of fierce debate among scholars and industry pundits (Fthenakis et al., 2009; PricewaterhouseCoopers, 2010). The extant literature falls short of providing a comprehensive assessment of solar power that considers the three key dimensions influencing the competitiveness of solar electricity generation: technology, time and location. Deriving one consolidated view based on existing studies is impossible as they use diverging methods and mainly inconsistent assumptions. We address this gap by exploring the question: What is the competitiveness of leading solar technologies depending on time and location?

Our assessment is based on a qualitative analysis fed by an extensive literature review and expert interviews as well as detailed techno-economic modeling. The latter allows us to compare the LCOE (levelized cost of electricity) of the three currently leading large-scale solar technologies (crystalline silicon photovoltaics, cadmium telluride photovoltaics and concentrating solar power) in five locations for 2010 and 2020.

We show that in 2010 solar technologies cannot yet compete with the benchmark set by a combined cycle gas turbine (CCGT). In a comparison of solar technologies in 2010, PV CdTe ranks 1st, PV c-Si 2nd and CSP 3rd, with PV c-Si 10–13% more expensive than PV CdTe and CSP 25–45% more expensive than PV CdTe. However, in 2020 solar LCOE in favorable locations (US, Spain) come close to parity with CCGT. Despite an attractive solar resource in China and Egypt, solar LCOE in those countries are still not yet competitive mainly due to relatively high discount rates that reflect country risk premiums. Figure 4 shows that in 2020, none of the solar technologies emerges as a clear winner in terms of LCOE: Driven by the integration of storage, CSP outperforms PV in the US and Egypt. The LCOE differences between CSP and PV CdTe range from –10% to 9%. The delta between PV CdTe and PV c-Si remains stable, PV c-Si being 10–14% more expensive. Also, the qualitative assessment along seven dimensions[8] does not yield a winning technology.

[8] (1) Technological uncertainty, (2) transmission costs, (3) storage potential 6-16 hours, (4) resource bottlenecks, (5) addressable market, environmental impact and (7) local value creation/employment opportunities.



a DNI in Germany (~2 kWh/sqm per day) is not sufficient to effectively operate a CSP plant. Scholars usually cite a threshold of 5 kWh/sqm per day
b 15.6 excluding storage

Figure 4: Levelized cost of electricity in 2020 by country, EUR$_{2020}$ cents/kWh

In summary, our findings indicate that large-scale solar power technologies will rely on government intervention for many years to come. Therefore smart policy is required on global and national levels to further increase the competitiveness of solar power. We derive four recommendations for policymakers from our results. First, future policy support should incentivize innovators to exploit the technology-specific learning potentials in the field of PV and CSP technologies. Second, in order to efficiently deploy large-scale solar technologies, it is key to exploit the solar resource available in sunbelt countries. Third, policymakers should incentivize technology providers and investors to make use of PV and CSP technologies' location-specific strengths. This would also increase the efficiency of policy support. Fourth, policymakers need to evaluate whether there are strategic co-benefits that increase the political feasibility and stability of the substantial funding required to support solar technologies.

5.2 The impact of technology-push and demand-pull policies on technical change - does the locus of policies matter?

How to design public policies in order to trigger clean technology innovation is a highly relevant question given challenges such as climate change (e.g., Mowery et al., 2010). While comprehensive empirical evidence suggests a positive effect of technology-push and demand-pull policies on innovation (e.g., Taylor et al., 2005), it is far less understood how the geographic locus of such policies affects innovation. The vast majority of studies have exclusively concentrated on the impact of domestic policies without accounting for a potential effect of foreign policies (e.g., Johnstone et al., 2009). However, for policymakers it is important to understand to what extent domestic policy funding also impacts foreign innovators – and vice versa – and thus creates country-level innovation spillovers. Where such spillovers exist, the national benefits of domestic policy funding may not be sufficient to justify this funding in the first place. Since the few studies on the innovation effect of foreign policies provided inconclusive results (Dechezleprêtre and Glachant, 2011; Popp, 2006) this paper addresses the question of how the innovation effects of domestic and foreign demand-pull and technology-push policies differ.

Our econometric panel analysis of the solar photovoltaics (PV) case based on patent data of 15 OECD countries in the period 1978 to 2005 yielded three key findings: First, the analysis shows that domestic technology-push policies trigger innovative output exclusively within national borders. Second, domestic and foreign demand-pull policies lead to innovative output in a country. Third, there is no indication that market growth induced by domestic demand-pull policies results in more innovative output than market growth induced by foreign demand-pull policies.

We argue that the country-level innovation spillovers from demand-pull policies may be due to technology characteristics of solar PV. Future research that addresses the impact of domestic and foreign policies on innovation should take such characteristics into account to further develop the theory. From the standpoint of a national policymaker, our results suggest that demand-pull policies should be applied rather carefully in order to limit innovation spillovers. In contrast, technology-push policies might be helpful in improving a nation's competitive advantage through the creation of domestic innovations. From a global perspective, there is a risk that spillovers disincentivize policymakers to invest in demand-pull policies, which could prove harmful for the development of global markets. Hence there is a need to create supranational demand-pull policy schemes that ensure a continuous market development and that address the spillover issue.

5.3 The effect of demand-pull policies on innovation in different technology life-cycle stages – the case of wind power

In recent years, demand-pull policies have been widely applied as a means to diffuse clean technologies that have to overcome market failures and structural rigidities (IEA, 2004, 2007). Environmental economists have come to the conclusion that, in addition to diffusion, demand-pull policies also 'induce' innovation (Jaffe et al., 2002). However, in quasi-evolutionary approaches to technical change, the demand-side is assumed to be a necessary rather than a sufficient condition for innovation (Dosi and Soete, 1988). Under certain conditions the development of the supply-side is marked by phases of high and low diversity and follows a technology life-cycle (Abernathy and Utterback, 1978; Anderson and Tushman, 1990; Klepper, 1997). Since scholars argue that diversity is conducive to innovation (Cohen and Malerba, 2001; Stirling, 1998, 2007), diversity appears to be an important supply-side factor which should be scrutinized when analyzing the relationship between demand-pull policies and innovation. However, the extant empirical literature either assumes diversity to be *constant over time* (e.g., Johnstone et al., 2009) or *steadily diminishing over time* (e.g., Junginger et al., 2010).

Approximating diversity with different life-cycle stages, this paper therefore addresses the question of how demand-pull policies impact innovation in different phases of the technology life-cycle. We apply an econometric panel analysis of the wind power case based on patent data from 15 OECD countries in the period 1978 to 2002. The concept of paradigms is used to model diversity and to differentiate the technology life-cycle of wind power in an era of competing paradigms and in an era of a dominant paradigm.

The regression results suggest that the causal effect between demand-pull policies and innovation is not *constant over time*: The impact of demand-pull policies on innovation in the era of competing paradigms is weaker than in the era of a dominant paradigm. There is even evidence that demand-pull policies have a negative effect on innovation in the era of competing paradigms.

While there are several explanations for why our analysis yields a weaker innovation effect of demand-pull policies during the era of competing paradigms than during the era of a dominant paradigm, there seems to be only one effect that could explain why at times demand-pull policies may have a negative effect on innovation: Demand-pull policies potentially exerted 'selective' pressures on competing wind power paradigms since primarily one paradigm (which later emerged as dominant) benefited from policy-induced returns to adoption. Hence demand-pull policies might have reduced diversity in the era of competing paradigms and thus contributed to a decline in innovation. However, 'selection' is not necessarily inefficient but also generates positive standardization effects such as economies of scale. For this reason, policymakers should consider the trade-off between standardization and diversity (David and Rothwell, 1996; Stirling, 2007; Tassey, 2000; Van den Bergh, 2008) when applying demand-pull policies during an era of competing paradigms. After a dominant paradigm has emerged, demand-pull policies no longer have an adverse effect on diversity and are therefore generally well-suited to foster innovation.

5.4 The two faces of market support – how deployment policies affect technological exploration and exploitation in the solar photovoltaic industry

Most clean energy technologies that are capable of addressing environmental concerns such as climate change cannot yet compete with conventional energy technologies based on fossil fuels. Therefore it is a highly relevant question how policy support can drive technical change in the field of clean energy technologies (e.g., Mowery et al., 2010). In recent years deployment policies (also referred to as demand-pull policies) have been very widely used to diffuse clean energy technologies. It is widely accepted that such policies also foster innovation (e.g., Kemp et al., 1998; Newell et al., 1999). However, the extant literature dealing with the innovation effect of deployment policies either uses highly aggregate measures of innovation (environmental economics, e.g., Cleff and Rennings, 1999) or chooses a systems perspective (quasi-evolutionary approaches, e.g., Nill and Kemp, 2009). Such studies do not focus on the detailed mechanisms on an actor-level (e.g., firms) through which deployment policies impact innovation. Indeed, there are indications that deployment policies might create a suboptimal balance of technological exploitation and exploration on a firm-level (Nemet, 2009). In contrast to previous studies, this paper chooses the firm as a unit of analysis and can therefore address the question of how deployment policies affect corporate investments in technological exploration and exploitation. We use an inductive approach and derive propositions based on 9 case studies (interviews with 24 corporate managers) with European, US, Chinese and Japanese firms that produce solar photovoltaic (PV) modules. 16 interviews with leading PV industry experts are used as complementary evidence.

Three key findings emerged from our analysis. First, there are indications that policy-induced market growth triggers an absolute increase in the level of firms' investments in exploration since it attracts venture capital and increases firms' financial resources through sales. Second, the extent to which deployment policies incentivize firms to invest in exploitation depends on the maturity of a firm's product. In case firms pursue more mature technologies, an increase in policy-induced market growth reduces the pressure to innovate through explorative activities and creates an incentive to shift scarce human resources from explorative towards exploitative activities. Yet firms pursuing less mature technologies tend to increase exploitative activities to a lesser extent in the case of an increase in policy-induced market growth since they lack a commercial product or at-scale production equipment. Third, as exploitation enables benefits from learning-by-doing and economies of scale, strong policy-induced market growth raises market entry barriers for less mature technologies.

These findings translate into important implications for the design of deployment policies. While deployment policies generally foster technological innovation, for two reasons policymakers should not incentivize strong exploitative firm behavior through excessive market growth. First, if firms underinvest in exploration, i.e., R&D, more market volume may be required to achieve a certain level of technical progress. This results in higher cost to society, which in the worst case could stall future policy investments in PV due to public acceptance issues. Second, exploitative behavior of firms can increase the risk of locking in a distinct PV technology that is inferior to emerging technologies and that might not become competitive in the long-term.

6 Conclusions

A massive acceleration of technical change in the field of clean energy technologies is essential to address the climate change challenge. It is widely acknowledged that smart technology policy is a crucial ingredient to spark this acceleration. This dissertation's objective is therefore to derive recommendations for smarter technology policy by addressing the following question:

How can technology policy foster technical change in the field of clean energy technologies?

Below the most important contributions of this dissertation are synthesized. On this basis implications for policymakers – the primary objective of this research – and corporate mangers are deduced. This dissertation concludes by pointing out important avenues for further research.

6.1 Contributions

Four key contributions emerge from this dissertation, including empirical and theoretical elements. First, this research addresses a gap very recently pointed out by Prof. Edenhofer (2011), an IPCC lead author: "[There is] a striking dearth in reliable peer-reviewed data on what it costs to generate renewable electricity and what determines those costs.". Paper I provides holistic data on the competitiveness of large-scale solar technologies in different countries across four continents in 2010 and 2020. It also addresses the issue of grid integration by analyzing storage cost of intermittent solar electricity. The results underscore that presently and likely at least for another decade policy support is a prerequisite for the deployment of any leading large-scale solar technology. In addition, transparency regarding the current life-cycle stage of solar power technologies is provided. This is a valuable input to policymaking (see paper IV).

Second, this dissertation contributes to insights into the geographical dimension of technology policy by indicating that the innovation effect of domestic demand-pull policies does not necessarily only occur within national borders. For the case of solar PV paper II finds that policy-induced market growth abroad has at least the same innovation effect in a country as domestic policy-induced market growth. Yet based on the Porter Hypothesis (Porter, 1991; Porter and van der Linde, 1995) and the literature on user-producer interaction (Lundvall, 1985; Lundvall, 1988) instead a weaker innovation effect of foreign demand-pull policies would have been expected. This is important food for thought for future theory building and empirical studies.

Third, this dissertation departs from the implicit assumption in the extant literature that a single, time-invariant causal effect between demand-pull policies and innovation is at work (e.g., Johnstone et al., 2009). For the case of wind power paper III shows that the technology life-cycle stage is an important moderator of the relationship between demand-pull policies and innovation. While the innovation effect of demand-pull policies is positive during times of low technological diversity (era of a dominant paradigm), it is weaker – if not negative – during a phase of high diversity (era of competing paradigms). Therefore, future theoretical work ought to incorporate technological diversity as a crucial factor in conceptualizing the 'innovation inducement' effect of demand-pull policies.

Fourth, this dissertation contributes to a better understanding of the detailed causal mechanisms through which demand-pull policies impact technological learning on a firm-level. Findings from the case of solar PV propose that it is essential to distinguish between different kinds of technological firm-level learning when analyzing the impact of demand-pull policies since the latter may have a differential effect on explorative and exploitative learning (paper IV). While strong policy-induced market growth is likely to increase the absolute level of exploration, it may incentivize firms to increase their relative investments in exploitation. Moreover, the technological maturity of a company's products could influence the degree to which demand-pull policies trigger firm investments in different types of learning. This highlights the importance of complementing macro-level research on technology policy and technical change with a micro-level perspective that considers the heterogeneity of firms (Nelson and Winter, 1982).

6.2 Policy implications

Today, the vast majority of wind and solar power applications cannot yet compete with conventional power generation based on fossil fuels. This research shows that at least for large-scale solar power plants, substantial policy-induced technical change is essential to reach competitiveness around 2020 in favorable locations (paper I). Obviously, reaching competitiveness is a prerequisite if solar power is to supply more than 50% of the world's electricity 50 years from now as very recently outlined in a scenario by the International Energy Agency (Bloomberg, 2011). In line with previous studies, the results of this thesis show that technology-push policies and demand-pull policies generally trigger innovation and hence represent an intriguing opportunity to close the competitiveness gap. However, the results of papers I – IV have also exposed some basic risks inherent in faulty design and misuse of technology policy. If these risks materialize, they could reduce the innovation impact of technology policy or at worst even hamper technical change: Inefficient policy schemes can result in considerable cost to society, which can cause public acceptance problems with clean energy technologies. Furthermore, under specific circumstances demand-pull policies may even generate technological lock-ins, in which the 'wrong technology' is picked as a winner. Finally, demand-pull policies can cause country-level innovation spillovers (paper II), which may disincentivize policymakers to invest sufficiently in such policies.

Mitigating these potential risks is essential to exploit the potential for technical change that can be induced by technology policy. Below four policy recommendations that contribute to more efficient and effective technology policy are presented. First, policymakers can increase the efficiency of demand-pull policies by choosing country-technology combinations with the lowest gap to competitiveness. Second, preventing excessive policy-induced market growth increases the efficiency of demand-pull policies and reduces the risk of technological lock-ins. Third, country-level innovation spillovers have to be addressed, for instance, through supranational coordination of demand-pull policy schemes. Fourth, an adequate balance between technology-push and demand-pull policies ought to depend on country and technology characteristics.

6.2.1 Increasing focus on most competitive country-technology combinations

The results of paper I suggest that the competitiveness of solar technologies (and other RETs) strongly depends on location factors. For example, the electricity generation costs of a solar PV power plant in the Southwest US are around 45% lower than in Germany due to differences in solar irradiation. In addition, the location-specific strengths of RETs differ. In the case of solar power, in most locations solar PV tends to have a competitive advantage over concentrating solar power, while this rank order might switch in locations with a higher share of direct sunlight and a closer proximity to the equator (e.g., Southern Egypt). This implies that in certain countries a certain type of renewable power is closer to competitiveness with conventional power generation than in alternative country-technology combinations. Therefore, when policymakers would like to foster technical change with demand-pull policies in a technological field such as solar power, they should focus on country-technology combinations that are closest to competitiveness in order to reduce cost to society. For instance, in 2010 the required feed-in tariff per kWh of large-scale solar PV power in Germany is around three times higher than in the Southwest US (paper I). It appears highly inefficient that Germany has been the leading market for solar PV in recent years. Doubtless the German demand-pull policy funding was a key driver in sparking the emergence of a global solar PV industry, which potentially is a very important actor in the battle against climate change. However, from a global perspective, it would have been substantially more efficient if, for example, California had taken on this task. In the future it will be indispensable to avoid excessive cost to society through inefficient country-technology combinations in the course of the urgently needed 'energy turnaround'. Otherwise, lack of public acceptance may jeopardize the entire endeavor.

6.2.2 Preventing excessive policy-induced market growth

In general this research suggests that demand-pull policies have a positive impact on innovation (papers II – IV). They trigger learning-by-searching as they stimulate the interest of venture capital investors and increase firms' financial resources through sales (paper IV). In addition, such policies foster learning-by-doing and learning-by-interacting (paper III).

However, against the underlying assumptions of the widely applied learning curve model[9] paper IV suggests that beyond cumulative production also the intensity of market growth impacts technological learning. This has important implications for policymaking, since in case demand-pull policies induce excessive growth like in the Californian Wind Rush in the 1980s or in the PV industry in recent years two major risks arise. First, the findings in paper IV indicate that strong market growth can incentivize firms to shift their balance between exploitation and exploration towards exploitation, i.e., they may increase their focus on production-related activities to reduce cost and may deprioritize R&D. This exploitative behavior of firms implies that likely more market volume is required to achieve a certain amount of technical progress. Consequently, society pays more for one unit of technical progress. Given the considerable investments needed to reach the competitiveness of RETs – in particular of solar power – such additional cost could reduce the public acceptance of RETs and thus increase the risk that policymakers and society opt against such investments.

Second, according to the results in papers III and IV, strong policy-induced market growth can create technological lock-ins. In times of high diversity (i.e., typically during an era of competing paradigms), demand-pull policies can exert selection pressures (see also Faber and Frenken, 2009). Since primarily commercial technologies benefit from demand-pull policy-induced learning, the competitiveness gap between emerging and commercial technologies widens. Hence, demand-pull policies bear the risk of 'selecting' a commercial design that in the long run may prove inferior to emerging designs and will not reach competitiveness with conventional energy technologies. Such a lock-in, again, could cause public acceptance issues since it considerably increases the necessary investments to reach competitiveness. It appears that policymakers face a trade-off when using demand-pull policies in times of high diversity. On the one hand, demand-pull policies induce learning and standardization effects such as economies of scale. On the other hand, selective pressures created by demand-pull policies may block promising avenues for innovation through premature technological lock-ins (Arthur, 1989). Before applying demand-pull policy schemes, policymakers should therefore attempt to gain transparency on the 'option value' of diversity in a technological field. The 'option value' is high if the uncertainty about the future competitiveness of different technological paradigms is high. In this case policymakers should rather cautiously invest in demand-pull policies to keep selective pressures low. In addition, policymakers can counterbalance these pressures by applying technology-push policies (e.g., public R&D funding) that maintain and promote diversity.

One could argue that excessive growth is required given the urgency of the climate change challenge. Yet even a moderate annual growth rate of 20%, for example, would allow solar PV to supply 50% of world electricity consumption around 2040. With an annual growth

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[9] It assumes learning to be a function of cumulative production, irrespective of the speed at which it has accumulated over time.

rate of 40%, this threshold would be reached only 12-14 years earlier. It seems unlikely that the advantages of a high growth path such as increased greenhouse gas abatement and additional contributions to structural transformation to a low-carbon power sector would outweigh the significant opportunity costs and possible resistance from the public.

6.2.3 Addressing the issue of country-level innovation spillovers

While paper II suggests that the innovation effect of domestic technology-push policies only accrues to national innovators, in the case of domestic demand-pull policies both national and foreign innovators benefit. These country-level innovation spillovers might act as a disincentive for policymakers to invest in demand-pull policies. The extent of spillovers likely depends on technological characteristics: In some technological fields the proximity between innovator and market may be crucial. For example, Danish wind turbine manufacturers in the early 1980s learned from field tests and mutual interaction in their home market – a key factor for their global success afterwards (paper IV). However, such learning seems to be less important for producers of solar PV (paper II).

If substantial innovation spillovers exist as in the case of solar PV (paper II), policymakers may not sufficiently invest in demand-pull policies to ensure continuous market growth, which is essential to exploit the considerable potential of solar PV in the longer term. Continuous growth ensures investor interest, enables cost reductions and contributes to a structural change towards a low-carbon power sector. Although policymaking across multiple nations is challenging (cf. slow progress towards a global climate policy), a supranational demand-pull policy scheme (e.g., as planned by the European Union) could indeed balance the effects of innovation spillovers and thus minimize disincentives for investments in this policy type. Furthermore, such a scheme could include a focus on the most competitive country-technology combinations (see 6.2.1). A strategy on the national level to mitigate spillovers involves increased investments in technology-push policies: First, policymakers improve the national competitiveness in a technological field with the help of technology-push policies (e.g., public R&D funding). Then demand-pull policy funding is intensified. Due to its increase in competitiveness, the domestic industry will benefit from a higher share of demand-pull policy funding and its positive innovation effects.

6.2.4 Balancing technology-push and demand-pull policies

While there is no silver bullet for the optimal allocation of technology-push and demand-pull policies, this research underscores that policymakers ought to consider the individual technology (see also Sagar and van der Zwaan, 2006) and country-specific factors when allocating funds to technology-push and demand-pull policies.

Regarding technological factors, the results of paper I suggest that the potentials of different types of learning vary by technology. For example, in the case of concentrating solar power (CSP) the scaling of plant size and R&D-driven technological breakthroughs are key levers for cost reduction, while R&D and scaling of production capacity primarily contribute to cost decreases of solar PV. It appears that deployment of capacity beyond demonstration projects is less important for cost reductions in CSP than in solar PV. Therefore, compared to solar PV, technology-push policies seem to be relatively more important for CSP, whereas demand-pull policies are relatively less important – and vice versa for PV.

Also, country factors influence the adequate balance of the technology policy types. Ultimately the political feasibility of investments in technology policy also depends on the cost and the benefits they induce – and these vary by country. This can be exemplified by demand-pull policies. Where a demand-pull policy scheme entails co-benefits in a country beyond technical change such as local value creation (paper I) and relatively low innovation spillovers (paper II), public acceptance is more likely than without such co-benefits. As for cost, demand-pull policy schemes for a specific technology tend to be more feasible in countries where the competitiveness gap is relatively small (paper I). Overall, policymakers should take a close look at the co-benefits and specific cost of demand-pull policies when considering their use.

In conclusion, the long-term effectiveness of technology policy largely depends on the benefits and cost it creates. If policy funding induces high cost due to inefficiencies (excessive growth, suboptimal country-technology combinations, inadequate balance of technology-push and demand-pull policies) or causes an incongruence of benefits and cost (country-level innovation spillovers), policymakers may hasten to contain cost to society by cutting back or even phasing out funding. However, this would likely disrupt the evolution of clean energy technology industries and hamper technical change. Therefore policymakers should increase the efficiency of technology policy in order to avoid unnecessary cost to society and – more importantly – ensure urgently needed technical change in the field of clean energy technologies.

6.3 Managerial implications

This dissertation has focused on deriving implications for policymaking. Yet an improved understanding of the relationship between technology policy and technical change can prove valuable from a managerial standpoint. Below, three recommendations for corporate managers with a focus on the solar power industry are presented. First, managers should closely interact with policymakers to shape technology policy. Second, to ensure long-term success, a focus on fundamentally attractive country-technology combinations is essential. Third, managers of solar PV module manufacturers ought to consider the management of uncertainty as well as technological advances as key levers to generate a sustained competitive advantage.

6.3.1 Shaping technology policy

Since solar power is unlikely to become competitive before 2020 (paper I), policy is and will continue to be a key variable in each business model of firms active in the solar industry. As technology policy has not been without its flaws in the past (see 6.2), corporate managers as well as policymakers should engage in improving it – for the sake of their own companies. Managers possess considerable know how concerning the potential for technical change (paper I) and the impact of technology policy on technological learning in their companies and on an industry level (paper II). Both can serve as valuable input into the policymaking process. However, in the short-term firms have an incentive to withhold such information to exploit existing policy schemes. For example, a feed-in tariff, which is significantly higher than current levelized cost of solar PV electricity results in very attractive margins for PV companies along the value chain. Still, managers have to be aware that this short-term arbitrage might come with a considerable backlash when policymakers cut back feed-in tariffs and/or cap overall funding to limit public cost. Therefore, in their own interest, managers should 'educate' policymakers at least to a certain extent in order to ensure that technology policy is efficient and thus viable in the long-term. In addition, a closer interaction with the policymaker would give managers more insight into the policymaking process, which would in turn facilitate the anticipation of future policies. In conclusion, managers should engage in the shaping of technology policy in order to improve its quality and to decrease regulatory uncertainty.

6.3.2 Focusing on fundamentally attractive country-technology combinations

In the short-term, arbitrage of existing policy schemes is a key success factor for firms active in the solar power industry. However, in the past such schemes tended to be highly uncertain, requiring firms to quickly adapt to new regulatory conditions. Particularly in countries where absolute and specific costs (per kWh) for solar feed-in tariffs are high (e.g., in Germany), future market development remains uncertain with a rather dim long-term outlook. Therefore firms should establish or enlarge their footprints in markets that are less dependent on policy support. While for example the US solar power market is still in its infancy, it is likely to develop more continuously and dynamically than the German market since it requires significantly less demand-pull policy funding to trigger a certain amount of installed capacity (regulatory leverage). The difference in regulatory leverage between these two markets will even increase further as the levelized cost of electricity (LCOE) decreases.[10] In addition, solar power technologies in the Southwest US might approach competitiveness with conventional power generation around 2020 (paper I). Were a certain country-technology combination to reach 'sustainable markets'. the upside in terms of market development would be considerable (First Solar 2011). In sum, firms are well advised to exploit today's 'subsidy markets'. However, they should start positioning themselves in future 'sustainable markets'.

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[10] Today the regulatory leverage of solar PV in the Southwest US is roughly 2 (1 EUR demand-pull policy funding triggers 2 EUR private investment) and 1.3 in Germany. Assuming the LCOE decreases by 33%, the regulatory leverage in the US would increase to 4 (+100%) and in Germany to 1.6 (+25%).

6.3.3 *Differentiating through uncertainty management and technological advances*

Firms in the solar industry should strive to achieve a sustained competitive advantage by focusing on two levers. First, they have to be capable of managing the high level of regulatory and technological uncertainty in the solar industry (paper IV). Regulation is constantly changing and induces demand-side risk, whereas on the supply-side it is still uncertain which technology will emerge as a dominant design. As pointed out in 6.3.1, engagement in the policymaking process helps to reduce regulatory uncertainty. In addition, vertical integration could prove beneficial to balance margin fluctuations along the value chain. Technological uncertainty could be hedged via venture or R&D investments and a diligent monitoring of competing design approaches. Finally, to weather the demanding conditions in the solar industry, firms should make sure to have a very robust capital base in place.

Second, firms ought to concentrate on technology advances as a key differentiator. Mainly focusing on exploitative activities to reduce costs such as scaling of production capacities (paper IV) is unlikely to assure a sustained competitive advantage. Competitors with a sufficient capital base can easily imitate such a strategy. Choosing a low-cost production location does not serve as a long-term differentiator either. Also marketing capabilities are unlikely to serve as a differentiator in a very cost driven industry. Therefore firms should have a strong focus on their R&D activities to gain a competitive edge in their product technology. This recommendation is consistent with the strategy chosen by the two currently leading manufacturers of solar PV modules in terms of market capitalization: First Solar and Sunpower. These companies have continuously had R&D intensities above industry standard.

6.4 Further research

This dissertation fills some white spots on the map depicting the relationship between technology policy and technical change. However, further research in this field is of paramount importance given both the limitations of this dissertation and previous studies as well as the urgency and complexity of the climate change challenge. A review of the framework underlying this research (Figure 2), the results presented in the individual papers and the conclusion of this dissertation point towards four fruitful avenues for further research: i) A more granular conception of technology policy (dependent variable) could improve our understanding of its impact on technical change; ii) Technology characteristics require more scrutiny as they seem to influence the relationship between technology policy and technical change; iii) Future research should attempt to extend its scope of analysis more often to technical change as a whole (dependent variable) instead of focusing on specific building blocks of technical change such as innovation; iv) Last but not least, beyond the analysis of distinct technologies, a systemic perspective on technical change needs greater attention.

First, this dissertation has differentiated between type and locus of technology policy (paper II, III) and has analyzed policy-induced growth as a basic design element of demand-pull policies (paper IV). Yet, in addition, the detailed characteristics of policy instruments are an important determinant of technical change (Taylor et al., 2005). In recent years particularly feed-in tariffs have become a popular instrument among policymakers to drive the diffusion of clean energy technologies. Scrutinizing different feed-in tariff systems regarding their technical change impact and potential co-benefits (e.g., local value creation) would help to improve the design of such schemes and to benchmark them with alternative instruments. Researchers ought to also focus on the question how feed-in tariffs could transition to market prices when clean energy technologies approach competitiveness. In addition, the interaction of different policies should receive greater attention, as typically a variety of different instruments in the fields of technology-push and demand-pull policies are applied (see Fischer and Preonas 2010 for a detailed research agenda).

Second, the impact of technology characteristics on the relationship between technology policy and technical change (e.g., Sagar and van der Zwaan, 2006) requires greater scrutiny. Such research would allow policymakers to better tailor policy instruments to specific technologies. This dissertation has identified the life-cycle stage as a single technology characteristic that influences the impact of demand-pull policies on innovation in the case of wind power (paper III). It would be worthwhile to replicate this analysis for additional technologies since the impact of demand-pull policies on selection mechanisms potentially leading to a dominant paradigm likely differs by technology. Case studies on the impact of demand-pull policies on exploitation and exploration (paper IV) in other technological fields could further complete the understanding on the risk of technological lock-ins when applying demand-pull policies. Moreover, the importance of different learning mechanisms may vary between technologies. This should be reflected in the allocation of public funds to technology-push and demand-pull policies given that different policy types induce technical change via various learning mechanisms (e.g., technology-push policies primarily trigger learning-by-searching). Paper I provides some initial insights in this regard. Furthermore, paper II proposes that learning mechanisms and other technology characteristics could impact the degree of country-level innovation spillovers. Cross-technology analyses based on methods similar to those in paper II-IV would prove very fruitful in gaining a more robust and comprehensive understanding of how technology characteristics affect the link between technology policy and technical change.

Third, a main focus of this dissertation is innovation, which is a key building block of technical change. However, in future research the scope of analysis should be extended to technical change. Innovation is not fully capable of measuring a technology's competitiveness. For example, standardization effects resulting from a decrease in diversity also drive technical change. These include, among other factors, economies of scale and network externalities. Therefore, to better understand the effect of demand-pull policies on technical change, it is essential to further examine the trade-off between standardization and diversity (e.g., Stirling, 2007). One particular challenge in this context is the differing time lags between the effects of standardization (rather quick) and innovation (rather slow) on technical change.

Fourth, technical change within a distinct technology such as wind or solar power strongly depends on technical change on a systemic level. This research focused on a technology level without taking into account interactions between different technologies on a system level. Future research in the field of clean energy technologies should also choose a system level perspective to better understand synergies between technologies and the requirement for enabling technologies. For example, a particular challenge in the global power sector is to match the intermittent supply of renewable electricity with demand patterns. Thus far researchers in social science have not paid sufficient attention to technologies that enable further innovation and diffusion of RETs. Therefore future research should investigate the role of grid and storage technologies in fostering technical change in the power sector.

7 Overview of the papers

All four papers shown in Table 3 are included in Annex I as published by the journal or as submitted to the journal. The submission status of the papers is as of October 31, 2011.

Table 3: Overview of the papers included in this dissertation

	Title	Authors	Journal	Status
I	Shedding light on solar technologies – a techno-economic assessment and its policy implications	Peters, M. Schmidt, T.S. Wiederkehr, D. Schneider, M.	Energy Policy, 2011 39 (10): 6422-6439	Published
II	The impact of technology-push and demand-pull policies on technical change - does the locus of policies matter?	Peters, M. Schneider, M. Griesshaber, T. Hoffmann, V.H.	Research Policy	Resubmitted
III	The effect of demand-pull policies on innovation in different technology life-cycle stages – the case of wind power	Peters, M. Hünteler, J. Schneider, M. Hoffmann, V. H.	Industrial and Corporate Change	Submitted
IV	The two faces of market support – how deployment policies affect technological exploration and exploitation in the solar photovoltaic industry	Hoppmann, J. Peters, M. Schneider, M. Hoffmann, V. H.	Research Policy	Submitted

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Annex I – Individual Papers

PAPER I

Shedding Light on Solar Technologies – A Techno-economic Assessment and its Policy Implications

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Abstract

Solar power technologies will have to become a major pillar in the world's future energy system to combat climate change and resource depletion. However, it is unclear which solar technology is and will prove most viable. Therefore, a comprehensive comparative assessment of solar technologies along the key quantitative and qualitative competitiveness criteria is needed. Based on a literature review and detailed techno-economic modeling for 2010 and 2020 in five locations, we provide such an assessment for the three currently leading large-scale solar technologies. We show that today these technologies cannot yet compete with conventional forms of power generation but approach competitiveness around 2020 in favorable locations. Furthermore, from a global perspective we find that none of the solar technologies emerges as a clear winner and that cost of storing energy differs by technology and can change the order of competitiveness in some instances. Importantly, the competitiveness of the different technologies varies considerably across locations due to differences in, e.g., solar resource and discount rates. Based on this analysis, we discuss policy implications with regard to fostering the diffusion of solar technologies while increasing the efficiency of policy support through an adequate geographical allocation of solar technologies.

Keywords: photovoltaics (PV); concentrating solar power (CSP); technology policy

1 Introduction

Society is facing serious problems such as climate change, resource depletion, and pollution. To meet these challenges a 'technology revolution' (Galiana and Green, 2009) in the field of clean energy technologies is required in order to decouple economic growth from adverse environmental impacts. Solar power has the potential to become a protagonist in this 'revolution'. According to forecasts of the International Energy Agency, solar technology could contribute 20% to global electricity generation in 2050 (IEA, 2010a). However, in 2010 the share of solar power has been well below 0.5% as the cost of solar technologies cannot yet compete with other forms of electricity generation. Significant innovations in solar power technologies are a prerequisite to unlocking the enormous potential of solar energy. A wide set of solar technologies is available in the field of photovoltaics (PV) and concentrating solar power (CSP) with differing performance characteristics.

Which technology is and will prove most viable in our electricity systems is heavily contested among scholars and industry experts (Fthenakis et al., 2009; PricewaterhouseCoopers, 2010). While the competitiveness of solar power generation differs by technology, time and location the extant literature lacks a holistic assessment of solar power based on these three dimensions. Integrating existing studies into one overall picture is not possible since they rely on a variety of methods and mostly inconsistent assumptions. Hence, there is a clear need to holistically and accurately assess key solar technologies on a common basis to guide users, investors, technology providers and policymakers in terms of investment and policy funding. In this paper we concentrate on recommendations for future policymaking as policy is likely to be the single most important lever to lead solar power towards competitiveness.

In order to provide a sound basis for our policy discussion (see Section 6), this paper, therefore, focuses on the following research question: What is the competitiveness of leading solar technologies depending on time and location? Building on Tushman and Rosenkopf (1992), we assess solar technologies based on their key merit dimensions. While the levelized cost of generating and storing electricity (LCOE) is undisputedly the most important dimension of merit, qualitative aspects of solar technologies also impact their overall competitiveness. Therefore, we will focus more specifically on the following four sub research questions:

1) In 2010, how do PV and CSP technologies compare in terms of LCOE?

2) In 2020, how will PV and CSP technologies compare in terms of LCOE?

3) How do 2010 and 2020 LCOE of PV and CSP technologies change depending on local financing and weather conditions in present and future leading solar markets?

4) How do PV and CSP technologies compare along qualitative merit dimensions?

Methodologically, we construct a LCOE model, which is capable of quantifying the generation as well as the storage cost of PV and CSP electricity. To assure accuracy we choose a high degree of granularity in the input data. For projections we use a combination of bottom-up and top-down estimates (Neij, 2008). The qualitative evaluation of the remaining merit dimensions is conducted based on an extensive literature review and expert interviews.

This paper is structured as follows: In the subsequent Section, we provide a short overview of solar technologies and markets. In Section 3 the existing literature on techno-economic assessments of solar power technologies is reviewed. We describe the method and assumptions used in Section 4. Based on the results, presented in Section 5, we derive policy recommendations in Section 6 before concluding in Section 7.

2 An overview of solar technologies and markets

Solar power technologies can be divided into two main classes: photovoltaics (PV) and concentrating solar power (CSP). PV exploits the photovoltaic effect exhibited by semiconductors and thus directly converts solar irradiation into electricity. CSP systems use mirrors to focus sunlight onto a receiver in which a fluid (e.g., thermo oil or molten salt) is heated up to several hundred degrees Celsius. In a heat engine (e.g., a steam turbine) this thermal energy is then converted into electricity (Jacobson, 2009).

2.1 Photovoltaics

Since the patenting of the first solar cell in 1954 two principal types of PV technologies have emerged: wafer based crystalline silicon (c-Si) and thin film. While the former typically had market shares of 80-90% in previous years, recently thin film technologies have been gaining ground. Even though the efficiencies of thin film modules are poorer, their cost per watt is lower due to less material usage (Bagnall and Boreland, 2008). In particular, cadmium telluride (CdTe) based modules have been successful lately due to their low cost position. Their market share increased from 1% in 2005 to 9% in 2009 (Photon, 2010). Other commercial thin film technologies such as copper indium gallium selenide (CIGS) and thin film silicon also increased their market shares in recent years. Dye sensitized (Graetzel, 2001) and organic solar cells (Brabec and Sariciftci, 2001) have developed quickly. However, these technologies are still in a pre-commercial phase (Photon, 2010). In addition, in the coming decades, so called third generation photovoltaics have the potential to lower the levelized cost of electricity by combining thin film approaches with high efficiency concepts (Green, 2006).

Although annual PV capacity additions have grown, on average, with more than 40% since 2000 (EPIA, 2010a), it is still at a very low level compared to globally installed power plant capacity (Figure 1). Driven by an attractive feed-in tariff scheme effective since 2000, Germany has gained a 42% share in installed PV capacity while only accounting for 3% of globally installed power plant capacity (Figure 1). Following the German example, other European countries have also introduced PV feed-in tariffs incentivizing capacity additions. In the past, PV policy support was rather limited outside of Europe resulting in a low non-European share of the world market. However, PV policy support is currently expanding globally which will lead to an increasing share of non-European PV markets – particularly in China and the US (EPIA 2010).

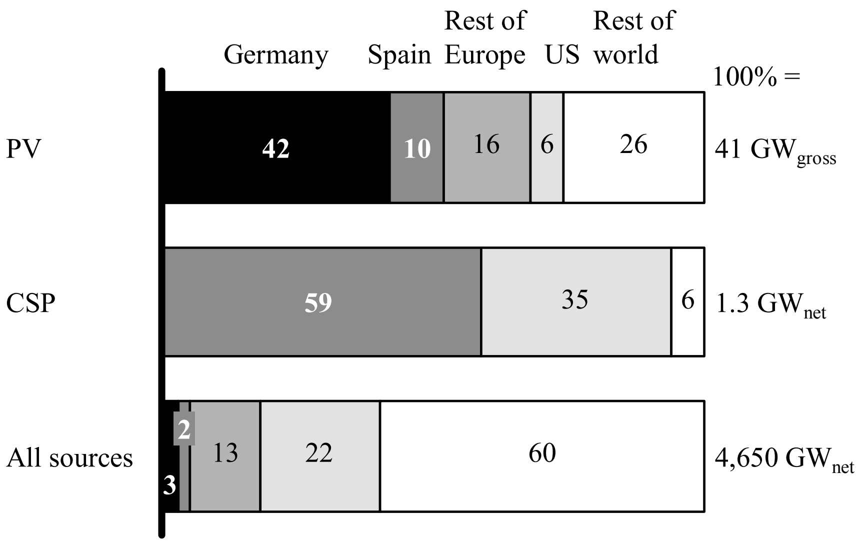

Figure 1: Share of globally installed capacity in 2010 by countries/regions, in percent; Source: Energy Information Administration (2010), EPIA (2010a), Emerging Energy Research (2010) and Solarbuzz (2011)

In contrast to the market for PV installations, the production of solar cells – the key component of PV plants – mainly occurs outside of Europe. In recent years Asia has emerged as the major production hub for solar cells, accounting for more than ~60% of global production in 2009 (Photon 2010). Amongst other factors, this has been driven by favorable energy and labor costs as well as deep expertise in semiconductor technology. The majority of innovative activity in the field of PV technology has also occurred outside of Europe in recent years, with US, Japanese and Chinese inventors accounting for more than 50% of international patent families (Peters et al., 2011). While it was chiefly large technology providers (like Siemens) and energy companies (such as Shell and BP), which were the first to establish industrial scale production lines in the field of PV, at present the leading PV technology providers are mainly pure-play firms (e.g., First Solar, Suntech Power, SMA). Only in Japan have industry conglomerates such as Sharp or Sanyo been investing in PV technology for several decades.

2.2 Concentrating solar power

In the 1980s the first industrial scale CSP systems were built in the Mojave Desert using the parabolic trough design, which has remained the incumbent CSP design with market shares above 90% until today (CSP Today, 2010). However, three alternative CSP designs exist: tower, linear fresnel and dish engine. In a CSP tower, plant heliostats concentrate irradiation on one single receiver atop a tower. Due to the central receiver such systems benefit from higher steam cycle temperatures and lower energy transport requirements than parabolic trough plants. Yet land requirements are significantly higher (Kaltschmitt et al., 2007). CSP plants using fresnel reflectors focus sunlight on an elevated linear receiver. Compared to a parabolic trough plant, linear fresnel systems exhibit lower costs for reflectors and structural support at the expense of lower solar-to-electric efficiencies (Purohit and Purohit, 2010). Dish engine systems consist of large mirror dishes and a receiver integrated with a combustion engine (e.g., a sterling engine) at the focal point of the dish. While dish engine systems are the most modular CSP design, investment cost and land use are high (Trieb, 2009).

As of 2010 1.3 GW of CSP capacity had been installed worldwide–significantly less than in PV (Figure 1). The majority of CSP capacity is installed in Spain, due to a favorable feed-in tariff (REN21, 2010) . However, future capacity additions are very likely to occur mainly outside of Europe since other geographies benefit from more favorable irradiation conditions and since Spain has capped annual CSP installations at 500 MW. In the US a multiple gigawatt (GW) project pipeline is expected to be executed in the coming years. Additionally the Middle East, North Africa, China and India all offer growth prospects for CSP (REN21, 2010).

CSP system and component providers are mainly based in Germany, Spain and the US. While German and Spanish CSP companies focus largely on the parabolic trough design (e.g., Siemens and Abengoa), US headquartered firms rather rely on power tower (e.g., Brightsource) and linear fresnel technology (e.g., Ausra). Until recently primarily startups and medium sized enterprises developed CSP technology. Yet since 2009 several leading European technology providers have invested in CSP firms: Siemens bought Solel, Areva acquired Ausra and Alstom invested equity in Brightsource.

3 Techno-economic assessment of solar power technologies – a review of the literature

There is a variety of studies on the techno-economic assessment of solar technologies. A focus of these analyses has been on the levelized cost of electricity since it is the key competitiveness metric for fossil-fired and renewable power generation technologies (Rubin et al., 2007; Sunpower Corporation, 2008). We compiled a comprehensive review of the recent literature, which uses LCOE as a metric in assessing solar power technologies (Table 1), allowing us to identify crucial research gaps. The aggregate analytical scope of the literature reviewed is quite broad. Analyses have focused on the three key determinants of LCOE, i.e., technology, time and location. Some studies complement the quantitative assessment with qualitative merit dimensions: Technological uncertainty (Sargent and Lundy, 2003), the addressable market (e.g., PricewaterhouseCoopers, 2010; Trieb et al., 1997), quality of electricity (e.g., Estela, 2010) and water requirements (e.g., PricewaterhouseCoopers, 2010; Trieb, 2009) are evaluated.

Integrating the existing studies into one overall picture is not possible since they rely on a variety of methods and partly inconsistent assumptions. In addition, some determinants of LCOE require further scrutiny. Eventually we identified four research gaps: First, there is a lack of literature assessing and comparing the two leading solar technologies, i.e., PV c-Si and PV CdTe on a granular level. Second, although most studies in the field of CSP include energy storage in their analyses (e.g., German Aerospace Center, 2006), this is not common in the field of PV–even though the intermittency of PV electricity is a major challenges of this technology (Trieb, 2009). Only very recently have scholars begun to analyze storage options such as compressed air energy storage (CAES) and batteries (Estela, 2010; Mason et al., 2008) for PV. Third, while some scholars have run sensitivity analyses to understand the impact of variations in discount rate on LCOE (Pitz-Paal et al., 2005), location-specific realistic discount rates have not yet been included in LCOE analyses. Fourth, the extant literature also offers room for further enhancements of methodological rigor. Concerning the future cost reduction potential of solar technologies the majority of studies presented in Table 1 solely rely on a top down learning curve approach (IEA, 2010c; Kost and Schlegl, 2010), yet such a method is exposed to very high uncertainty in the field of solar technologies (Neij, 2008; Nemet, 2006). In addition, some studies are not very transparent regarding the underlying assumptions. For example, it is often unclear whether real or nominal price levels are used or whether CSP production figures are based on gross power sold, or net power after adjustment for purchased electricity.

As a result of technological uncertainty as well as the use of differing methods and assumptions, it is heavily contested among scholars and industry experts, which technology is and will prove most viable in electricity systems. Some years ago scholars agreed that the LCOE of CSP parabolic trough systems is significantly below that of PV plants (Quaschning, 2004; Trieb et al., 1997). This is also supported by the feed-in tariffs granted under the Spanish Royal decree 661 in 2007 and 2008 (Del Río González, 2008). However, significant cost reductions in the field of PV eliminated the former consensus (Sarasin, 2010). In very recent studies results tend to be conflicting. For example, according to PricewaterhouseCoopers (2010) CSP LCOE is significantly below PV LCOE whereas Fthenakis and colleagues (2009) consider PV to be more competitive than CSP[1] in terms of LCOE. Furthermore, studies do not reach a consistent picture regarding the competitiveness of solar technologies with fossil based electricity generation. According to Estela (2010) and Trieb (2009) PV[2] and CSP will reach competitiveness with gas-fired power plants between 2015 and 2020, while the IEA (2010b, c) expects competitiveness of PV and CSP plants past 2020. Assessing solar power generation technologies on a common basis and in a granular manner can help to shed some light on the research gaps presented above.

[1] 2007, excluding storage, California.
[2] Excluding storage.

Table 1: Literature review on techno-economic assessment of solar power technologies

Publication	Scope of LCOE analysis		
	Technology (storage)[a]	**Time**	**Variation of location variables (weather data, discount rate)**
Sargent and Lundy (2003)	CSP: parabolic trough, tower (yes)	2004, 2006, 2010, 2015, 2020	No
Quaschning (2004)	CSP: parabolic trough (no) PV: not specified (no)	2004, 2014	Weather data
Pitz-Paal et al. (2005)	CSP: parabolic trough, tower, dish engine (yes)	2005, 2020	Weather data; Discount rate (sensitivity analysis)
German Aerospace Center (2006)	CSP: not specified (yes)	2000 – 2050	Weather data
Ummel and Wheeler (2008)	CSP: not specified (yes)	2012-2020	No
Gerbert and Rubel (2009)	CSP: parabolic trough (?) PV: thin film (no)	2008	No
Trieb (2009)	CSP: parabolic trough (yes) PV: not specified (no)	2000-2050	Weather data (only CSP)
Fthenakis et al. (2009)	CSP: not specified (yes) PV: CdTe (yes)	2007, 2015, 2020	No
Landesbank Baden-Württemberg (2009)	CSP: not specified (?) PV: CdTe, CIGS/CIS, a-si/μ-si[b], c-Si	2008 – 2020	Weather data (only for unspecified PV)
Pricewaterhouse-Coopers (2010)	CSP: parabolic trough, tower (no) PV: not specified (no)	2010	Weather data (only CSP)
Purohit and Purohit (2010)	CSP: parabolic trough, tower (yes[c])	2007 (tower), 2009 (parabolic trough)	Weather data (only Indian locations)
Sarasin (2010)	CSP: parabolic trough, linear fresnel (no) PV: c-Si, CdTe (no)	2010	No
Izquierdo et al. (2010)	CSP: parabolic trough, tower (yes)	2005	No
Estela (2010)	CSP: not specified (yes) PV: not specified (yes)	2010-2025	Weather data
EPIA (2010b)	PV: not specified (no)	2010, 2020, 2030	Weather data
IEA (2010c)	PV: not specified (no)	2008, 2020, 2030, 2050	Weather data
IEA (2010b)	CSP: not specified (yes)	2010-2050	Weather data
Kost and Schlegl (2010)	CSP: parabolic trough, tower (yes) PV: not specified (no)	2010-2030	Weather data; Discount rate (sensitivity analysis)
Key message	No study models all leading solar technologies[d] incl. storage (i.e., PV c-Si, PV CdTe, CSP parabolic trough) • 1 study compares leading PV designs[d] (e.g., c-Si and CdTe) • 2 out of 18 studies analyze PV storage solutions	Most studies (13 out of 18) project future LCOE (some up to 2050)	No study accounts for deviations in country risk *and* weather data when modeling different locations • 12 out of 18 studies vary weather data • 2 out of 18 studies conduct sensitivity analyses of discount rates (no modeling of country risk)

a Type of solar technology modeled, in brackets: information regarding whether storage is modeled.
b Amorphous and micromorph silicon. c Tower: storage < 1 h. d In terms of capacity installed.

4 Methodology

The subsequent Section is very comprehensive in order to be transparent about our methodological approach. We scrutinized large-scale solar power plants based on the leading solar technologies (PV c-Si[3], PV CdTe and CSP parabolic trough)[4] by conducting a quantitative and qualitative techno-economic assessment. We identified cost and quality of electricity as the key merit dimensions, which we analyzed based on a LCOE model. The cost of energy storage is also included in the model as the storage capabilities of a power plant determine the quality of electricity. Concerning financing we assumed an unleveraged financing of the power plant assets. The discount rate is the pre-tax unsubsidized value in each country. We derived the following LCOE formula from the literature (Kost and Schlegl, 2010):[5]

$$\frac{\sum_{n=0}^{N} \frac{CAPEX + OPEX}{(1+i)^n}}{\sum_{n=0}^{N} \frac{kWh_{initial,net} \times (1-Degrade)^n}{(1+i)^n}} \tag{1}$$

where CAPEX (investment cost) and OPEX (operations and maintenance cost) represent cash outflows. The net electricity production[6] is determined by the initial production ($kWh_{initial,\ net}$) and the degradation factor (Degrade). *i* is the discount rate and *n* the plant lifetime.

To benchmark solar technologies we use the LCOE of a combined cycle gas turbine (CCGT). It is considered a reasonable yardstick for renewable electricity by public bodies in the US and Europe (California Public Utilities Commission, 2011; European Commission, 2010). In the US and in Europe gas-fired plants are projected to be the fastest growing non renewable source of electricity (Energy Information Administration, 2010). CAPEX assumptions are based on European Commission data (European Commission, 2008). In an upper LCOE bound we included a high CO_2 and gas price scenario, while for a lower bound we assumed no CO_2 prices and a low gas price scenario (see Appendix C for assumptions).[7]

In the subsequent Sections we outline the modeling of the key determinants of LCOE, which are dependent on technology, time and spatial parameters (Figure 2). In Section 4.1, we

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[3] There are two types of c-Si multicrystalline and monocrystalline. As multicyrstalline has the higher market share our analysis is based on multicrystalline silicon.

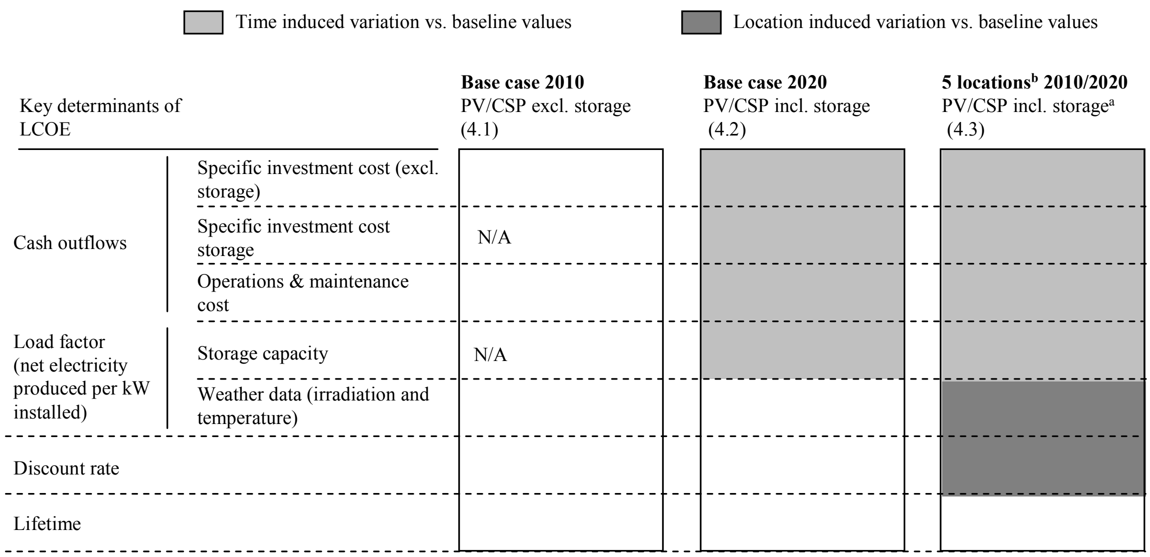
[4] We focused on large-scale solar power plants for two reasons. First, as CSP plants are of large scale[4] it allows for a fair comparison between CSP and PV technologies. Second, in 2010 "the trend toward large-scale PV plants continued around the globe" (REN21, 2010, p.19).

[5] A salvage value of 0 is assumed at the end of a plant's lifetime; potential LCOE reduction effects of carbon credits are not included since a CO_2 price is already reflected in the benchmark technology.

[6]It is assumed that electricity consumed at site is covered by electricity produced at site and not by purchased electricity.

[7] When comparing solar technologies with the benchmark two aspects should be considered. First, the quality of CCGT electricity is higher than of any solar technology: CCGT can offer full load at any time of the year while solar plants with storage at most locations are at times – particularly during the winter months – not

present the derivation of LCOE input data to assess PV and CSP plants excluding storage in a baseline location in 2010, namely Dagget (California, US). In Section 4.2, the methods used to project LCOE input data for solar power plants including storage built at the baseline location in 2020 are described. In Section 4.3, we provide details on the replication of the 2010 and 2020 LCOE analyses for additional locations in some of the largest current and/or future solar markets, i.e., China, Germany, North Africa and Spain. Finally in Section 4.4, we present how we qualitatively evaluated merit dimensions apart from generation and storage cost of electricity. For all operations and maintenance (O&M) cost an annual escalation in line with the long-term EUR inflation rate is assumed. Discount rates are also EUR inflation adjusted via the simplified Fisher equation (Fisher, 1930). All assumptions underlying the solar LCOE calculations are presented in the Appendix (Tables A.1-A.4 for PV technologies, Tables B.1-B.4 for CSP parabolic trough, Tables D.1-D.2 for general assumptions).



a 2010 excl. storage.   b Storage capacity of PV plants in Germany adapted to reach capacity factors in Spain.

Figure 2: Overview of levelized cost of electricity (LCOE) model

4.1 Assessing the baseline location in 2010

To construct a base case we calculated present (2010) LCOE values for PV c-Si, PV CdTe and CSP parabolic trough plants in Daggett (California, US). Daggett was chosen as a baseline location for two reasons. First, it is representative for the Southwest of the US, which is likely to become the largest solar market in the medium-term (REN21, 2010). Second, Daggett is amongst the locations with the best solar resource in the world and thus well-suited to calculate the performance frontier of solar technologies. Furthermore, we did not incorporate storage solutions in the 2010 base case since this is not standard practice within solar power plants at present. This is due to the high cost

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capable of operating at full load. Second, however, LCOE of CCGT plants heavily depends on fuel and CO_2 price developments and hence is more uncertain.

of storage, low penetration of intermittent solar power and favorable feed-in tariff schemes, which guarantee the buy-off of intermittent power (REN21, 2010).

For all solar technologies we assumed identical discount rates, which reflect typical return requirements in the power industries of industrialized countries (Salomons and Grootveld, 2003). Plant lifetime is chosen based on typical assumptions in the PV industry (EPIA, 2010b) and does not vary between technologies, 2010 and 2020, or location.

4.1.1 PV c-Si and PV CdTe

Specific cash outflows

Cash outflows per kW depend on investment cost consisting of component cost, project development and EPC[8] cost as well as O&M cost. While investment cost per kW of PV plants are usually quoted based on gross values under standard test conditions we use net capacity to be consistent with CSP parabolic trough capacity, which is typically provided in net values.[9] For PV c-Si and CdTe component price assumptions we relied on investor reports of leading PV module and inverter companies (i.e., First Solar, Yingli, Suntech Power and SMA). Since current PV component profit margins partly differ significantly by company and component we calculated two cases, one based on "as is" profit margins the other based on expected long-term profit margins by component.[10] Expenses for project development and EPC cost were derived from First Solar investor communication, the world's leading CdTe module manufacturer. O&M cost are taken from EPIA (2010b) and expressed as a fraction of the initial investment on an annual basis.

Specific electricity production

The initial PV electricity production per kW_{net} depends on the solar resource available at a certain location and the outside temperature. Global solar irradiation consists of two components: direct and diffuse irradiation. PV converts both types of irradiation into electricity. We calculated the amount of solar irradiation received by a fixed module with optimal tilt based on global solar irradiation data.[11] We derived an average annual weighted module temperature factor based on dry bulb temperature data (U.S. DOE, 2011) for PV c-Si and PV CdTe in our baseline location.[12] Since the initial net electrical energy output of PV plants per kW slowly decreases over time we assumed a typical annual degradation rate of PV c-Si and PV CdTe module capacity (Jordan et al., 2010).

[8] Engineering, procurement and construction.
[9] Differences between PV net and gross values are particularly driven by soiling and inverter losses.
[10] This particularly allows for the reflection of significant profit margin differences between PV c-Si and CdTe modules, thus better reflecting the intrinsic LCOE performance of PV c-Si and CdTe.
[11] Irradiation data was obtained from EnergyPlus weather data sets (U.S. DOE, 2011). It provides TMY (typical meteorological year) weather data with an hourly resolution for more than 2100 locations worldwide. Data is either based on long-term ground measurement or on satellite derived data in combination with ground measurement. We cross-checked irradiation data for our locations with specific project data (Cohen, 2008; Solar Millennium, 2008) and alternative meteorological data (Joint Research Centre European Commission, 2011; Meteotest, 2010). Deviations were below 15%.
[12] The temperature within PV modules can account for performance variations of more than 10%.

4.1.2 CSP parabolic trough

Specific cash outflows

We relied on investment cost data from the NREL Solar Advisor Model (NREL 2010), which splits up the cost of a wet-cooled 100 MW CSP parabolic trough reference plant in the Southwest of the US into roughly 50 cost items.[13] The profit margin of the EPC company is adapted to be in line with PV plants. Using scaling factors also provided by NREL (2010) we scaled the reference plant down to 50 MW–a typical size for a plant built in 2010 or in previous years. The NREL installation cost data is also consistent with the turnkey price of a recently commissioned CSP parabolic trough plant in the US, i.e., Nevada Solar One (64 MW). O&M cost data was taken from the European Commission (2007) and expressed as a fraction of the initial investment on an annual inflation adjusted basis.

Specific electricity production

Unlike PV, CSP only makes use of direct irradiation. The amount of solar resource that hits the solar field aperture of a CSP system is given by the DNI (direct normal irradiation). Irradiation data was obtained from EnergyPlus weather data sets (U.S. DOE, 2011). We fed the NREL SAM model (NREL 2010) with the assumed DNI to thermodynamically model the net electrical energy output of the CSP parabolic trough plant. We optimized the field sizes via iterative model runs, ultimately choosing the configuration with the lowest LCOE.[14]

4.2 Assessing the baseline location in 2020

A replication of the base case in 2020 yields two time induced variations. First, the specific investment and O&M costs of solar technologies decrease due to technical and industry evolution. Second, PV and CSP power plants are assumed to have storage. Given the high uncertainty around cost estimates based on learning curve data (Nemet, 2006) we used – whereeever possible – a bottom-up approach to estimate different sources of cost reduction (Neij, 2008). We considered three types of cost reduction: 1) R&D driven, i.e., technical improvements, 2) production driven, i.e., component cost reductions through economies of scale and learning-by-doing, and 3) scaling of power plant size (Sargent and Lundy, 2003). In the case of CSP we separately analyzed all three types. In the case of PV, R&D and production driven cost reductions were treated on an aggregate

[13] As there is hardly any information on profit margins in the CSP industry available we do not model profit margins separately as in the case of PV. However, we assume that implicit component profit margins in the NREL data are rather on the low end given that CSP in the US faces significant competition from other power technologies such as wind and PV.

[14] “SAM is based on an hourly simulation engine that interacts with performance, cost, and finance models to calculate energy output, energy costs, and cash flows.” (https://www.nrel.gov/analysis/sam/). In the case of CSP plants the SAM performance model also considers thermodynamic parameters. For each location (USA, Egypt, China and Spain) we integrated EnergyPlus weather data in the model and specified the type of storage (no storage, six h storage). We then iteratively optimized the solar field to generate the LCOE optimal plant design.

level for data availability reasons and cost reduction through scaling of plant size was not included due to the high modularity of PV power plants.

As the penetration of solar electricity increases, storage will become ever more important for grid integration and matching of demand and supply. We modeled a molten salt storage solution in the case of CSP. For CSP we assumed six h storage in all locations yielding load factors between 34% and 46%. For PV, a compressed air energy storage (CAES) is assumed, which is accepted as a low cost and widely available solution (Fthenakis et al., 2009). For each location we modeled PV CAES plants with six h storage thus reaching the same level of electricity quality.[15] Since scholars also model CSP plants with more than six h storage to approach base load profiles (e.g., Trieb et al., 2011) we, in addition, analyzed CSP and PV power plants with 16 h storage (see Appendix E).

4.2.1 PV c-Si and PV CdTe including compressed air energy storage

Specific cash outflows excluding storage

We estimated future component cost and profit margins on a granular basis and kept the share of project development and EPC in the total investment cost constant. O&M cost for PV plants was also kept constant in terms of the annual fraction of the initial investment. Below we outline the methods used to derive PV c-Si and CdTe module prices as well as inverter and other component prices including R&D and production driven cost reductions.

We projected 2020 PV c-Si module prices by modeling silicon, silicon to wafer and wafer to module cost and profit margins.[16] To calculate future PV CdTe module cost we used First Solar's cost roadmap including R&D and production driven cost reduction potentials until 2014. Beyond 2014 we chose a learning curve approach.[17] Profit margin assumptions correspond to long-term expected profit margins in 2010 (see 4.1.1)

For both PV c-Si and CdTe, 2020 inverter cost was calculated based on the SMA specific learning curve observed between 2005 and 2009 assuming long-term expected profit margins. Remaining balance of system cost (BOS) was assumed to develop according to the First Solar technology roadmap until 2014. Thereafter, unit cost reduction was projected based on a learning rate calculated using prior cost reductions in BOS[18]. Our overall PV system costs estimates (c-Si and CdTe) for 2020 appear to occupy a middle ground between more aggressive (Fthenakis et al., 2009) and more conservative projections (IEA, 2010c).

[15] As we do not model a CSP plant in Germany, we assumed the Spanish load factor (34%) for the PV plant in Germany.

[16] Silicon cost estimates are based on a medium-term forecast by LBBW (2009). Specific silicon utilization per watt is projected by accounting for higher efficiencies, thinner wafers and reduction in kerf loss (Mason, 2007). Silicon to wafer cost and wafer to module costs are forecasted by applying a typical PV c-Si learning rate.

[17] Based on 2005-2009 First Solar production data we computed a PV CdTe module learning rate, which we used to estimate cost reductions between 2014 and 2020.

[18] In addition, BOS cost reductions driven by increases in module efficiency are considered.

Specific cash outflows CAES

Scholars widely agree that CAES and pumped hydro storage are the lowest cost options for large scale daily cycle electricity storage (Calaminus, 2010; Hannig et al., 2009; Leonhard W. et al., 2009). Both technologies are frequently cited as options to store intermittent PV and wind power (e.g., Mason et al., 2008). In this study we modeled CAES since underground storage capacity (e.g., in caverns) is widely available across the globe (Calaminus, 2010; Huang et al., 2009; Succar and Williams, 2008; Taylor and Halnes, 2010). Furthermore, we assumed that in 2020 advanced adiabatic (AA) CAES will be available (RWE, 2010)[19]. We used cost data on a component level (turbine, compressor, thermal storage and balance of plant) to model the 2020 cost structure of AA-CAES (Mason et al., 2008; Pickard et al., 2009). Our estimates are roughly in line with top down assumptions of AA CAES investment cost (e.g., Zunft et al., 2006).

Specific electricity production

To model PV power plants with load factors in the range of CSP plants, we increased the size of the PV field without increasing the nominal capacity of the total plant. Based on hourly EnergyPlus irradiation data (2010) we calculated the amount of electricity fed directly into the grid (i.e., up to the nominal capacity) and the amount, which is stored beforehand. To calculate the electricity production of the PV plant the same method as in 4.1.1 was used. For electricity being channeled through storage the CAES efficiency factor was applied in addition.

4.2.2 CSP parabolic trough cost structure including molten salt storage in 2020

Specific cash outflows including molten salt storage

As in the case of PV we modeled future component costs on a granular basis and kept the share of project development and EPC in the total investment cost constant. O&M cost for PV plants was also kept constant in terms of the annual share of the initial investment. Below we present cost reduction potentials induced by R&D as well as by production and scaling of plant size.

Regarding R&D driven cost reduction, the most crucial technical lever to reduce cost per watt installed is an increase in steam cycle temperatures from what is today ~400° C to more than 500°C, which improves solar-to-electric efficiency. There are two technical pathways available to do so for which prototypes already exist (Archimede Solar Energy, 2011; Zarza et al., 2004). First, direct steam plants, second, plants in which salt is used as a heat transfer fluid. Since direct steam plants with storage units are still in an early research phase (Steinmann and Tamme, 2008) we modeled a molten salt system.[20] In addition, we assumed that today's two tank storage systems are

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[19] Compared to today's diabatic CAES technology this solution is likely to need no gas firing and round cycle efficiencies are significantly higher.

[20] Further technical measures include front surface mirrors, which improve the optical efficiency of the solar field. Overall, we assumed a solar-to-electric efficiency increase to 19% in the baseline location (see also Table B.3).

replaced with a one tank thermocline solution further reducing cost per watt installed (Price et al., 2002).[21]

Primarily production driven cost reductions in the solar field and the HTF are calculated using a learning curve approach (Trieb, 2009).[22] In contrast to PV, scaling of plant size is a crucial cost reduction lever in the case of CSP parabolic trough plants. The storage unit and the power block in particular benefit from larger plant scales. We used NREL scaling factors (2010) to model a plant size increase from 50 MW in 2010 to 300 MW in 2020.[23]

Specific electricity production

We used the NREL SAM model (NREL 2010) to calculate the electricity output of a CSP parabolic trough plant including six h of molten salt energy storage. An LCOE optimal solar field size was chosen (compare Section 4.1.2).

4.3 Comparative assessment of five locations in 2010 and 2020

Replicating the LCOE analysis for favorable locations (in terms of solar resource) in Spain, Germany, China and Egypt requires a variation in two input variables: discount rates reflecting local project risks and local weather conditions.[24] We assumed project risks to be the same in Spain, the US and Germany (Salomons and Grootveld, 2003) and used discount rates recommended by the UNFCCC for energy projects under the CDM in Egypt and China (UNFCCC, 2010). Local weather data was obtained again from EnergyPlus weather data sets (U.S. DOE, 2011). Based on this data we calculated location-specific temperature derate factors for PV plants. CSP solar-to-electric efficiencies are directly influenced by the amount of direct irradiation as well as the latitude determining the seasonality of irradiation. Therefore, using the NREL SAM model (2010) we iteratively optimized the solar field size of CSP systems in each location to always assure the lowest LCOE configuration.

[21] A single tank storage energy system, which uses a low-cost filler material to replace the more expensive molten salt (35% cost reduction$_{real}$). Using molten salt has further positive and negative effects on investment costs, which we assume to offset each other. On the one hand such systems offer additional cost reduction potentials since less molten salt is needed due to higher temperatures and heat exchangers can be displaced. On the other hand, higher temperatures could require the use of more costly materials and O&M costs could increase as at times gas firing might be needed to prevent molten salt from freezing in the receiver tubes.

[22] For the HTF and the solar field a 10 % learning rate$_{real}$ is assumed; for the power block a constant annual unit cost reduction of 2% is assumed as cost reductions$_{real}$ for steam power blocks are rather driven by developments of conventional electricity technology.

[23] The scaling effect is calculated as follows: (baseline plant cost) x (project plant size / baseline plant size)^(scaling factor); assumed scaling factors: solar field (1) except civil work (0.9), power block (0.8), HTF (0.9) except solar field piping and HTF fluid (1), storage (0.8) except storage fluid (1).

[24] In addition, construction and project development cost differ between locations as they are dependent on local labor and permitting cost. However, as these costs are below 20% of the total PV and CSP system prices we assumed these costs to be the same across all locations (NREL, 2010).

4.4 Qualitative assessment of technologies

In a first step we selected merit dimensions other than cost using archival as well as interview sources. Based on the literature reviewed in Section 3 (i.e., academic studies, industry reports) and three discussions with solar industry experts of about one hour each, we compiled seven qualitative merit dimensions: 1) technological uncertainty, 2) long distance transmission, 3) storage potential, 4) resource bottlenecks, 5) addressable market, 6) environmental impact and 7) potential for local value creation and employment. We chose these dimensions as they, according to the literature and industry experts, are or will become relevant for users, investors, technology providers and policymakers in terms of investment and policy funding. In a second step, we assessed PV c-Si, PV CdTe and CSP parabolic trough technologies along the above merit dimension using the same sources as in step one. For each dimension – if possible – the technology with a competitive advantage was selected based on industry expert knowledge.

5 Results

The results chapter is structured along the four research questions presented in chapter 1. In Sections 5.1-5.3 we compare the solar LCOE results against the CCGT benchmark. In 5.4 we conclude with the results of the qualitative assessment.

5.1 Baseline location 2010

Figure 3, showing the LCOE for Daggett-based PV c-Si, PV CdTe and CSP parabolic trough plants in 2010, yields two key insights. First, compared to the benchmark technology CCGT solar technologies are 80-200% more expensive. Second, assuming long-term profit margins of manufacturers the current competitive advantage of PV CdTe becomes apparent. In 2010 PV CdTe LCOE are 11% below PV c-Si and 20% below CSP parabolic trough. Due to the leading cost structure of PV CdTe systems CdTe module manufacturer First Solar can currently charge substantial profit margins. These results should contribute to resolving the current debate as to which solar technology is currently best in terms of LCOE.

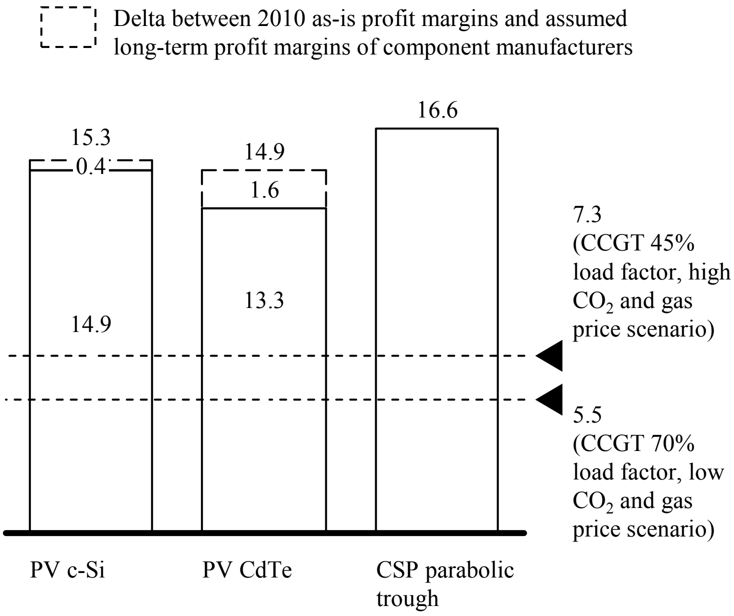


Figure 3: Levelized cost of electricity (excluding storage) in 2010, Daggett (US), EUR_{2010} cents/kWh

5.2 Baseline location 2020

Figure 4 shows the LCOE for Daggett-based PV c-Si, PV CdTe and parabolic trough plants in 2020. Three key findings emerge: First, solar technologies approach LCOE parity with CCGT due to decreases in solar LCOE and increases in the benchmark driven by rising gas and CO_2 prices. CSP parabolic trough plants including storage miss the upper bound of CCGT LCOE by less than 5%. Second, compared to the 2010 cost of PV and CSP peak electricity has decreased by 36-39%. Therefore, in terms of peak load PV CdTe clearly remains the leading technology. Third, however, the integration of six h storage significantly increases LCOE of PV c-Si (+37%) and PV CdTe (+39%), while CSP LCOE only increases by 4%. Including storage CSP now has an 18% cost advantage over PV c-Si and 9% over PV CdTe. In the case of 16 h storage this cost advantage is even more pronounced (see Appendix E).

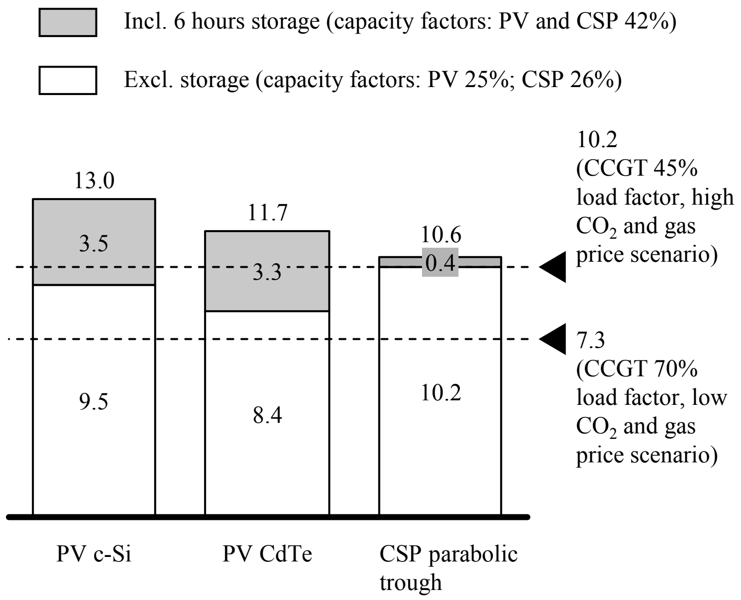


Figure 4: Levelized cost of electricity in Daggett (USA), 2020, EUR_{2020} cents/kWh

5.3 Different locations in 2010 and 2020

We now extend the analyses in Sections 5.1 and 5.2 to different locations. In Figure 5 and Figure 6 the 2010 and 2020 LCOE of PV c-Si, PV CdTe and CSP parabolic trough plants in present and future leading solar markets are exhibited. With regard to cross country comparison in 2010, the LCOE differences between the best (USA) and worst location (Germany)[25] reach almost to factor 2 driven by differences in weather conditions. However, due to disparities in local policy schemes Germany accounts for 40% and the US for only 7% of globally installed solar capacity (compare Figure 1).

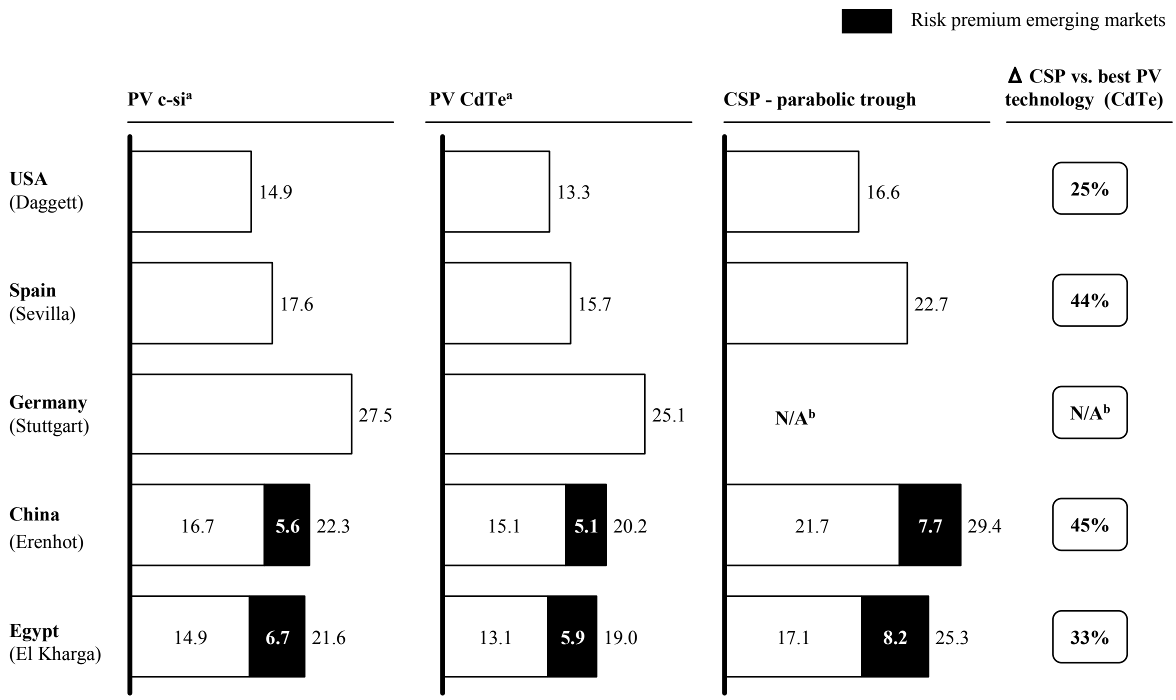
Although irradiation conditions in China and Egypt are favorable, LCOE in these locations cannot compete with US LCOE due to additional country risk premiums, which increases LCOE by 34-48%[26] and are caused by higher political, legal and regulatory uncertainties (UNEP and EcoSecurities, 2007). Excluding this premium, LCOE in the Egyptian location would be comparable to the US location. While the plants in the Spanish location do not have a country risk disadvantage, less favorable weather conditions result in LCOE being 18% (PV c-Si) to 37% (CSP) above US LCOE. The relative LCOE deltas between countries remain approximately stable until 2020.

With regard to the solar technology comparison in 2010, in all locations PV CdTe ranks 1st, PV c-Si 2nd and CSP 3rd, with PV c-Si being 10-13% more expensive than PV CdTe and CSP being 25-45% more expensive than PV CdTe. However, in the US and Egypt the competitive advantage

[25] Feed-in tariffs for large-scale open-space PV power plants ranged between 25.4 and 24.3 EUR cents/kWh in 2010. While this is below the c-Si LCOE value in Figure 5, a market for such installations still existed since investors accepted an unleveraged internal rate below 8%.

[26] The risk premium in China relates to private investments. State investments or investments being backed by the state, a common practice in China, will have a lower risk premium. For example, First Solar's 2 GW Ordos project is backed by the city of Ordos.

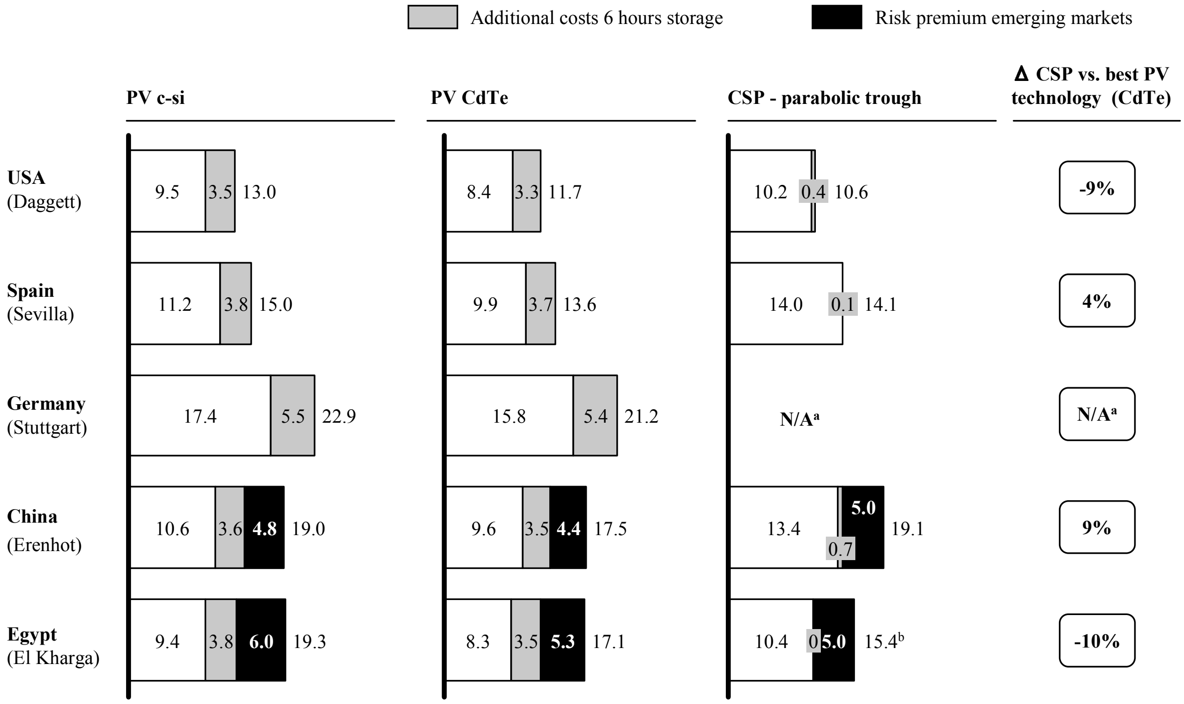
of PV over CSP is smaller than in Spain or China. This is due to higher solar-to-electric efficiencies of CSP in these locations caused by a higher share of direct irradiation and lower latitudes as well as higher temperatures reducing the efficiency of PV power plants. In 2020, driven by the integration of storage, CSP outperforms PV in two locations (US, Egypt). The delta between CSP and PV CdTe ranges from -10% to 9%. The LCOE difference between PV CdTe and PV c-Si remains stable PV c-Si being 10-14% more expensive.



a Based on assumed long-term inverter and module margins

b DNI in Germany (~2 kWh/sqm per day) is not sufficient to effectively operate a CSP plant. Scholars usually cite a threshold of 5 kWh/sqm per day

Figure 5: Levelized cost of electricity (without storage) in 2010 by country, EUR_{2010} cents/kWh



a DNI in Germany (~2 kWh/sqm per day) is not sufficient to effectively operate a CSP plant. Scholars usually cite a threshold of 5 kWh/sqm per day
b 15.6 excluding storage

Figure 6: Levelized cost of electricity in 2020 by country, EUR$_{2020}$ cents/kWh

Regarding the benchmark with CCGT in 2010, solar technologies in all locations are not yet competitive. This is illustrated by the fact that even in the US Southwest – the location with the lowest LCOE – (see Section 5.1) solar power cannot yet compete with CCGT. Even in geographies with relatively high gas prices such as Europe, the upper bound of our LCOE calculations remains below 10 EUR cents/kWh. In countries like, Egypt which have enacted fuel subsidies (Wuppertal Institut für Klima Umwelt Energie, 2006), CCGT LCOE are below the US level. In 2020, however, solar LCOE in the US and Spain approach parity with CCGT. While for the US this is already shown in 5.2, our analyses for Europe yield a CCGT LCOE band of 8.3 to 12.2 EUR cents/kWh, which is in the range of solar peak load LCOE in Spain. In Germany, solar LCOE is still clearly above the benchmark. Gas price forecasts for Egypt and China are not available. Yet even assuming the relatively high European benchmark, solar LCOE in Egypt and China do not yet reach parity with CCGT.

5.4 Qualitative assessment

In light of the close competition between solar technologies in the field of LCOE, a complementary qualitative assessment is important. The results of the qualitative analysis are presented in Table 2. There is also no clear winner amongst the technologies on a qualitative level. CSP parabolic trough has a competitive advantage in two out of seven dimensions (storage potential 6-16 h, long distance transmission, local value creation/employment). Vice versa also PV c-Si and CdTe outperform CSP in three out of seven dimensions (technological uncertainty, resource bottlenecks and addressable market). In the short- to medium-term there is no indication for issues that could severely challenge the technological evolution of PV c-Si, PV CdTe and CSP parabolic trough.

As in the case of LCOE, the relative competitiveness of CSP vs. PV improves at sites with a high and constant solar resource (e.g., Egypt, Southern California). At such sites the CSP parabolic trough could, in contrast to PV, generate more than medium load power at limited or no additional LCOE (see Appendix E). In addition, such locations are typically remote from load centers and thus require long distance transmission. This is cheaper for CSP parabolic trough plants where no local PV electricity storage is available.

Table 2 : Qualitative assessment of solar technologies; Source: The World Bank (2011); First Solar (2009); IEA (2009); Fthenakis (2009); Trieb (2009); Renewable Energy World (2010); Power Technology (2011); NREL (2011); German Aerospace Center (2006); Sargent and Lundy (2003); Estela (2010); Trieb et al. (1997); (Turchi et al., 2010); own calculations.

<table>
<tr><th>Merit dimension</th><th>PV c-Si</th><th>PV CdTe</th><th>CSP parabolic trough</th><th>Technology with competitive advantage</th></tr>
<tr><td>(1) Technological uncertainty</td><td colspan="2">• Power generation: track record of cost reductions; 41 GW_{gross} deployed;
• Storage: immature and costly; future cost downs highly dependent on (uncertain) technological breakthroughs</td><td>• 1 GW_{net} deployed; limited track record of cost reductions
• High share of future cost reductions based on technological breakthroughs (power generation and storage)</td><td>PV (c-Si, CdTe)</td></tr>
<tr><td>(2) Costs transmission over 3000 km (e.g., from Middle East/North Africa to Europe)</td><td colspan="2">• 10% of LCOE due to losses
• ~1 EUR cents/kWh for HVDC[a]; higher in case no storage at site possible due to lower utilization of HVDC</td><td>• 10% of LCOE due to losses
• ~1 EUR cents/kWh for HVDC equipment</td><td>CSP</td></tr>
<tr><td>(3) Storage potential 6-16 h</td><td colspan="2">• Yes, in geographies with high and constant solar resource
• Increase in LCOE</td><td>• Yes, in geographies with high and constant solar resource.
• Limited/no additional LCOE</td><td>CSP</td></tr>
<tr><td>(4) Resource bottlenecks</td><td></td><td></td><td></td><td>PV c-Si</td></tr>
<tr><td>Water</td><td colspan="2">• Negligible water consumption, aptitude for desert climates</td><td>• Wet cooled: high water consumption (~4,000 l/MWh), limited aptitude for desert climates
• Dry cooled (increases LCOE by 3-8%): low water consumption (300 l/MWh); aptitude for desert climates</td><td></td></tr>
<tr><td>Material for key Components</td><td>• Key materials (e.g., silicon) abundant</td><td>• Tellurium rare; yet, annual production potential > 100 GW likely</td><td>• Key materials abundant</td><td></td></tr>
<tr><td>(5) Addressable market</td><td></td><td></td><td></td><td>PV (c-Si, CdTe)</td></tr>
<tr><td>Modularity</td><td colspan="2">• Very high; useful for central (> 100 MW) and decentral energy systems (<10 kW, e.g., for rural electrification, roof top applications)</td><td>• Low; plant size > 50 MW</td><td></td></tr>
<tr><td>Geographies</td><td colspan="2">• Viable also outside of sunbelt due to use of direct and indirect irradiation</td><td>• Not viable outside of sunbelt as direct irradiation required</td><td></td></tr>
<tr><td>Combination with fossil-based power plants</td><td colspan="2">• Not possible</td><td>• Possible, e.g., solar field used to preheat steam in order to save fossil fuel</td><td></td></tr>
<tr><td>Slope angle restrictions</td><td colspan="2">• None</td><td>• Up to 2° possible</td><td></td></tr>
<tr><td>Side products</td><td colspan="2">• None</td><td>• Waste heat can be used for desalination, process heat and cooling</td><td></td></tr>
<tr><td>(6) Environmental impact[b]</td><td></td><td></td><td></td><td>None</td></tr>
<tr><td>Life cycle greenhouse gas emissions[c]</td><td>• Low: 2010 ~ 25 kg/MWh</td><td>• Very low: 2010 ~ 15 kg/MWh</td><td>• Very low: 2010 ~ 15 kg/MWh</td><td></td></tr>
<tr><td>Toxicity</td><td>• No/very limited use of toxic materials"</td><td>• Cadmium highly toxic; discharge very unlikely due to encapsulation in modules; recycling industry standard</td><td>• Thermo oil (at present standard heat transfer fluid) toxic. In the future, potentially to be replaced with non-toxic fluids (e.g., molten salt)</td><td></td></tr>
<tr><td>Land use[c]</td><td>• 99 kWh/sqm p.a.</td><td>• 72 kWh/sqm p.a.</td><td>• 96 kWh/sqm p.a.</td><td></td></tr>
<tr><td>(7) Local value creation/employment opportunities</td><td colspan="2">• High skilled work force: high (R&D, manufacturing)
• Low skilled work force: low (installation[d])</td><td>• High skilled work force: Medium (R&D, high-tech manufacturing)
• Low skilled work force: Medium (low-tech manufacturing, installation[d])</td><td>None</td></tr>
</table>

a High Voltage Direct Current (HVDC) line with 45% load factor. b For water consumption see resource bottlenecks.
c Values based on location in California, 2010. d Installation of CSP plant more labor intensive than installation of PV plant.

6 Policy implications

Solar power technologies will have to become a major pillar in the world's future energy system to mitigate environmental problems such as resource scarcity and climate change. However, large-scale solar technologies cannot yet compete with fossil-fired electricity generation technologies. Thus, in order to foster and exploit the 'solar option' smart policy action on global and national levels is required. Essentially, four aspects must be addressed that relate to the main variables analyzed above. First, further policy support should incentivize innovators to exploit the technology-specific learning potentials in the field of PV and CSP technologies. Second, capitalizing on the solar resource available in sunbelt countries is crucial in order to efficiently deploy large-scale solar technologies. Third, policymakers can increase the efficiency of policy support by incentivizing investors and technology providers to exploit location-specific strengths of PV and CSP technologies. Fourth, due to the substantial cost, which is still involved in supporting these technologies at present, policymakers need to assess whether there are strategic co-benefits that enhance the political feasibility and stability of such support. Below, we discuss these four dimensions by relying on the quantitative and qualitative results obtained. This allows us to provide policy recommendations on how to unleash the potential of solar power.

6.1 Improving solar power technologies

Our analyses show that solar power technologies in the US and Spain are likely to approach competitiveness with fossil-fired generation by around 2020. Hence, policy support will be indispensable until at least 2020 for enabling innovation and deployment in the field of solar technologies. This will involve the creation of markets (e.g., via feed-in tariffs) as well as public R&D funding. The results of our study also underscore the fact that a dominant design in the field of solar power technologies is not yet emerging: In 2020 the LCOE of different solar technologies are rather close and their absolute levels are subject to technological uncertainty. Also the qualitative assessment does not yield a technology with a clear competitive advantage. For the policymaker this implies a need to maintain and develop a variety of technologies, otherwise the risk of picking the "wrong" design as a winner increases.

Moreover, the policymaker should account for varying improvement potentials by technology, which implies the need for tailoring policy schemes to specific technologies. Regarding LCOE reduction we pointed out the three principal potentials: R&D driven, production driven and scaling of power plant size. We show that in the case of CSP the scaling of plant size from 50 MW to 300 MW and R&D efforts targeting technological breakthroughs are crucial to reduce LCOE. Hence, policymakers should – unlike in the Spanish feed-in tariff regime – enable and incentivize large plant sizes. In addition, public R&D funding is important to support the high risk, high return R&D projects which contribute to technological breakthroughs. While our analysis indicates that the scaling of PV power plants beyond 50 MW has little effect on LCOE, R&D

efforts and the scaling of production reduces LCOE. Finding an adequate balance between public R&D funding and deployment policies such as feed-in tariffs and designing more efficient deployment policy schemes in terms of innovation effect are the key challenges for policymaking in this context (Peters et al., 2011). In addition, the increasing share of solar and other intermittent renewable electricity calls for action: Policymakers ought to intensify policy support for storage and demand side management technologies, as well as enact regulations which simplify and incentivize the integration of such technologies into the grid, for example, dedicated public R&D funding for smart grid technologies and a feed-in tariff premium for stored electricity.

6.2 Efficiently deploying large-scale solar technologies by capitalizing on the solar resource

Our results clearly indicate that the location variables solar irradiation, discount rate and fuel prices heavily influence the competitiveness of solar power compared to a market benchmark. We show that the competitiveness of solar technologies is best in developed countries with a good solar resource and high fossil-fuel prices. Therefore, deploying solar power in the Southwest of the US or Spain is significantly more efficient than in Germany as it causes lower costs to society. In this respect the current distribution of installed PV capacity presented in 2.1 is highly suboptimal. Our 2010 LCOE results imply that in Germany the required feed-in tariff per kWh is around three times higher than in the Southwest of the US. While in the past in particular solar feed-in tariffs in Germany triggered the flourishing of the global PV market, in the years to come countries with an attractive solar resource should ideally drive the deployment of large-scale solar technologies.

Our analyses point out that relatively high discount rates and fuel subsidies put solar technologies at a significant disadvantage in emerging economies such as Egypt – despite their substantial solar resource. If these countries aim to develop a green growth strategy (Project Catalyst, 2010), for example under the UNFCCC, several levers could be pulled to increase the attractiveness of solar technologies. Our analyses indicate for example that excluding country risk premiums solar LCOE in Egypt would be comparable to the level in the US Southwest. Thus, policymakers should focus on reducing or taking over project risks in emerging countries in order to improve LCOE. Governments of emerging economies could act as investors themselves as illustrated by the Chinese state, employ governmental low-interest loans and provide state guarantees in combination with an international insurance for long-term power purchase agreements (Trieb et al., 2011). A second important lever is the gradual removal of fossil fuel subsidies, which is however an intricate endeavor. All these activities could be internationally supported, e.g. via the Clean Technology Fund of the World Bank or the Green Climate Fund established under the UNFCCC. Also bilateral support from developed countries is conceivable. For some developed countries with a limited solar resource there is a particular rationale to provide financing as they could import solar electricity from emerging economies in the sunbelt (e.g., within the scope of the DESERTEC project).

6.3 Exploiting location-specific strengths of PV and CSP technologies

For policymakers an understanding of the location-specific strengths of different solar technologies is key in order to focus on the most competitive technology for the respective location. In this context, three key findings emerge from our research. First, in locations with a relatively high share of diffuse irradiation, medium average temperature and a latitude of above 35 degrees such as Spain and Inner Mongolia in China our research suggests that policymakers and investors should focus on PV technologies. Second, locations with a high share of DNI, high temperatures and low latitude such as the Southwest of the US or Egypt are relatively favorable for CSP. In 2020 CSP is more competitive than PV in such locations if storage is included in plants. In addition, our research indicates CSP, in contrast to PV, can offer storage at no or only very limited additional costs in such locations. Hence, in these geographies CSP should account for a substantial share in the solar portfolio. However, water scarcity in the Southwest of the US and in North Africa could require CSP plants to be air-cooled, increasing LCOE by around 3-8% vs. wet-cooled systems (Turchi et al., 2010). Third, the choice of solar technology depends on the value of storage at a specific location. If solar power is deployed in a market with a low share of intermittent electricity where storage is not yet required PV is more attractive than CSP due its lower peak load LCOE. If the share of intermittent electricity, however, is high and thus storage is valuable CSP gains a competitive edge due to its limited LCOE increase due to storage.

6.4 Strategic search for co-benefits to increase political feasibility of solar power

To lead solar technologies towards competitiveness significant policy support is still needed, which will be paid for society. Therefore, political feasibility of solar support plans might be limited due to public acceptance issues. The results of our qualitative assessment are helpful in deriving three strategic co-benefits, which could increase the political feasibility of solar power. First, the diffusion of solar technologies in a country has the potential to offer local value creation and employment opportunities in R&D, manufacturing and installation. To exploit this potential a country should consider its specific competences when selecting a solar design. For example, if labor in a country is rather low skilled and low cost, CSP could offer more local value creation and employment opportunities than PV since CSP is more labor intensive and requires a less skilled workforce than in the case of PV. If a country lacks key competencies to establish a successful domestic industry in the field of PV or CSP, it could strive for acquiring such competencies through, e.g., funding public R&D or other capacity-building measures before investing significant funds in market creation. If successful, such strategies could allow a country to increase local value creation.

Second, solar power cannot only be deployed centrally in large-scale plants, but -in the case of PV- also in highly modular decentral generation units. It is widely accepted that in the emerging and least developed countries rural electrification can significantly contribute to economic development. As a result, in such countries policymakers should not exclusively focus on large-scale applications but also on rural electrification to generate 'high value' electricity.

Third, on an international level policymakers could strive for finding synergies between industrial strategies. The Desertec project is potentially a prominent example for bilateral synergies in this context. European states are likely to pay the majority of policy support needed to realize the project. This 'investment' translates into business for the companies in the Desertec consortia. In addition, Europe benefits from excellent irradiation conditions and low labor cost in the Middle East North Africa (MENA) region. Conversely, MENA states will gain from additional power supply, local value creation and employment. On the multilateral level, i.e., especially within the UNFCCC discussions, countries should develop roadmaps for the diffusion of solar technologies, reflecting their specific situation regarding natural resources, and social and techno-economic aspects. International institutions such as the Technology Executive Group or the Green Climate Fund, which are to be founded according to the Cancun agreement, should then coordinate and in the case of non-OECD countries financially support these activities.

7 Conclusion

This paper addressed a gap in the current discussions on the potential role of solar power technology in the world's energy systems by providing a comparative assessment of the three leading large-scale solar technologies in 2010 and 2020 as well as for different locations. We show that today these technologies cannot yet compete with conventional forms of power generation but approach competitiveness around 2020 in favorable locations. In addition, we find that none of the solar technologies emerges as a clear winner and that costs of storing energy differs by technology and can change the order of competitiveness in some instances. Importantly, the competitiveness of the different technologies varies considerably across locations due to differences in, e.g., solar resource and discount rates.

Based on these results we derive four policy implications. First, policy support should facilitate the implementation of cost reduction levers and enable the integration of solar technologies on a system level. Second, policymakers ought to increase the efficiency of policy support by particularly fostering solar market growth in countries with an attractive solar resource. Third, the exploitation of location-specific strengths of PV and CSP technologies could further increase the efficiency of policy support. Lastly, policymakers need to leverage strategic co-benefits of solar power deployment in order to enhance the political feasibility and stability of policy support.

In order to further refine policy recommendations, some areas for future research are especially promising. Policymakers need to be assisted by coming up with more precise advice on which policy mixes are most warranted to improve the different technologies, which are subject to different underlying learning mechanisms. In addition, while this study has shed light on the competitiveness of typical solar power plant projects, more detailed analyses of the total potential for these technologies in different countries are required. Lastly, future research should support policymakers in exploiting this potential by evaluating in more detail the needs for accompanying measures in the areas of storage and grid management.

Appendix A

Table A.1 : Investment cost PV power plant and adiabatic compressed air energy storage (AA-CAES)

	PV c-Si		PV CdTe		Source
	2010	**2020**	**2010**	**2020**	
PV power plant investment cost excl. storage, EUR/watt$_{gross}$	2.32	1.47	2.13	1.35	
Module price	1.23	0.77	0.89	0.56	See manufacturing costs & margins
Inverter price	0.19	0.16	0.19	0.16	See manufacturing costs & margins
Balance of system price (excl. inverter)	0.64	0.32	0.80	0.41	First Solar (2009), EPIA (2004), own assumptions & calculations
Project development cost, EUR/watt$_{gross}$	0.09	0.10	0.09	0.10	First Solar (2010a)
EBIT Engineering, Procurement and Construction (EPC)	0.19	0.12	0.17	0.11	See manufacturing costs & margins
PV power plant manufacturing cost & margins					
Module manufacturing cost CdTe, EUR/watt$_{gross}$ (excl. overhead)	N/A	N/A	0.54	0.34	First Solar (2010b), First Solar (2009), EPIA (2010a), First Solar annual reports 2005-2009, own calculations
Module manufacturing CdTe gross-margin	N/A	N/A	39%	39%	First Solar (2010b), own assumptions
Module manufacturing (vertically integrated) EBIT-margin	22%	22%	22%	22%	Yingli Green Energy (2011), own assumptions
Silicon manufacturing cost (incl. overhead)	0.12	0.06	N/A	N/A	Landesbank Baden-Württemberg (2009), Mason (2007), EPIA (2004)
Silicon manufacturing EBIT-margin	30%	30%	N/A	N/A	own assumptions
Silicon to wafer manufacturing cost (incl. overhead)	0.33	0.21	N/A	N/A	Landesbank Baden-Württemberg (2009), Strategies-Unlimited (2003), EPIA (2010a)
Silicon to wafer manufacturing EBIT-margin	15%	16%	N/A	N/A	own assumptions
Wafer to module manufacturing cost (excl. overhead)	0.40	0.26	N/A	N/A	Suntech Power (2010), Strategies-Unlimited (2003), EPIA (2010a)
Wafer to module manufacturing cost gross-margin	19%	19%	N/A	N/A	Suntech Power (2010), own assumptions
Wafer to module manufacturing cost EBIT-margin	11%	11%	N/A	N/A	Suntech Power (2010), own assumptions
Inverter manufacturing cost, EUR/watt$_{net}$ (excl. overhead)	0.16	0.14	0.16	0.14	SMA (2010); SMA annual reports 2006-09, EPIA (2010a)
Inverter manufacturing gross-margin	21%	21%	21%	21%	SMA (2010), own assumptions
Inverter manufacturing EBIT-margin	10%	10%	10%	10%	own assumptions
EPC-margin	8%	8%	8%	8%	own assumptions
Advanced adiabatic CAES investment costs (6 h storage)					
CAES turbo generator, EUR/watt$_{net}$		0.18		0.18	Mason et al. (2008)
CAES compressor, EUR/watt$_{net}$		0.16		0.16	Mason et al. (2008)
Balance of system (Compressor to generator ratio = 1)		0.12		0.12	Mason et al. (2008)
BOS % increase per increase of compressor to generator ratio by 1%		64%		64%	Mason et al. (2008)
Scale up factor PV power plant – US		1.85		1.80	own calculations
Scale up factor PV power plant – Spain		1.75		1.70	own calculations
Scale up factor PV power plant - Germany		2.75		2.75	own calculations
Scale up factor PV power plant - China		1.65		1.60	own calculations
Scale up factor PV power plant - Egypt		2.1		2.00	own calculations
Compressor to generator ratio - US		0.85		0.80	own calculations
Compressor to generator ratio - Spain		0.75		0.70	own calculations
Compressor to generator ratio - Germany		1.75		1.75	own calculations
Compressor to generator ratio - China		0.65		0.60	own calculations
Compressor to generator ratio - Egypt		1.1		1.00	own calculations
Cavern storage cost (6 h)/watt$_{net}$ installed		0.01		0.01	Mason et al. (2008)
Thermal energy storage (6 h)/watt$_{net}$ installed		0.36		0.36	Pickard et al (2009)
CAES investment cost US, EUR/watt$_{net}$		0.80		0.78	own calculations
CAES investment cost Spain, EUR/watt$_{net}$		0.77		0.76	own calculations
CAES investment cost Germany, EUR/watt$_{net}$		1.01		1.01	own calculations
CAES investment cost China, EUR/watt$_{net}$		0.75		0.74	own calculations
CAES investment cost Egypt, EUR/watt$_{net}$		0.86		0.83	own calculations

Table A.2 : PV power plant and AA-CAES operations & maintenance costs, construction time, plant size and lifetime

	PV c-Si		PV CdTe		Source
	2010	**2020**	**2010**	**2020**	
Operations & maintenance costs					
PV plant (excl. storage), share of investment cost p.a.	1.5%	1.5%	1.5%	1.5%	EPIA (2010b)
AA-CAES O&M fixed, EUR/kW_{net} p.a.	12	12	12	12	Gatzen (2005)
AA-CAES variable, EUR cents/kWh	0.56	0.56	0.56	0.56	Mason et al. (2008)
Inflation of O&M cost p.a.	2.1%	2.1%	2.1%	2.1%	Eurostat (2010)
Construction time					
PV power plant, months	6	6	6	6	own assumptions
CAES plant, months	24	24	24	24	own assumptions
Plant size, MW_{net}	50	300	50	300	own assumptions
Plant lifetime, years	25	25	25	25	EPIA (2010b)

Table A.3: PV – solar-to-electric efficiency

	PV c-Si		PV CdTe		Source
	2010	**2020**	**2010**	**2020**	
Module efficiency	14.0%	19.0%	11.2%	15.0%	First Solar (2009, 2010b), Suntech Power (2011), EPIA (2004)
Performance ratio excl. temperature effect	85.0%	85.0%	85.0%	85.0%	Haase and Podewils (2011)
Temperature derate factor					
US	91.1%	91.1%	94.1%	94.1%	U.S. DOE (2011), own calculations
Spain	92.4%	92.4%	95.0%	95.0%	U.S. DOE (2011), own calculations
Germany	97.8%	97.8%	98.6%	98.6%	U.S. DOE (2011), own calculations
China	97.3%	97.3%	98.3%	98.3%	U.S. DOE (2011), own calculations
Egypt	89.0%	89.0%	92.8%	92.8%	U.S. DOE (2011), own calculations
Solar-to-electric efficiency excl. storage					
US	10.8%	14.7%	9.0%	12.0%	own calculations
Spain	11.0%	14.9%	9.0%	12.1%	own calculations
Germany	11.6%	15.8%	9.4%	12.6%	own calculations
China	11.6%	15.7%	9.4%	12.5%	own calculations
Egypt	10.6%	14.4%	8.8%	11.8%	own calculations
Module degradation p.a.	0.5%	0.5%	0.5%	0.5%	Jordan et al. (2010)
AA-CAES round cycle efficiency		70.0%		70.0%	RWE (2010)
Share electricity via storage to grid					
US		23.6%		23.2%	U.S. DOE (2011), own calculations
Spain		16.8%		16.3%	U.S. DOE (2011), own calculations
Germany		23.8%		23.9%	U.S. DOE (2011), own calculations
China		14.9%		13.9%	U.S. DOE (2011), own calculations
Egypt		33.4%		31.7%	U.S. DOE (2011), own calculations
Solar-to-electric efficiency incl. AA-CAES					
US		13.7%		11.2%	own calculations
Spain		14.2%		11.5%	own calculations
Germany		14.7%		11.7%	own calculations
China		15.0%		12.0%	own calculations
Egypt		12.9%		10.7%	own calculations

Table A.4: Global solar irradiation, fixed tilt at optimal angle, kWh/sqm

	PV c-Si		PV CdTe		Source
	2010	2020	2010	2020	
US	2337	2337	2337	2337	U.S. DOE (2011), own calculations
Spain,	1951	1951	1951	1951	U.S. DOE (2011), own calculations
Germany	1180	1180	1180	1180	U.S. DOE (2011), own calculations
China	1960	1960	1960	1960	U.S. DOE (2011), own calculations
Egypt	2401	2401	2401	2401	U.S. DOE (2011), own calculations

Appendix B

Table B.1: Investment costs CSP parabolic trough

	2010	2020, excl. storage	2020, incl. storage	Source
Total Investment cost, EUR/kW$_{net}$				
US	3090	1909	3200	sum of components below
Spain, China	3313	2045	3468	sum of components below
Egypt	3090	1909	3468	sum of components below
Size of solar field, aperture area, sqm/kW$_{net}$				
US	5.6	4.6	8.6	NREL (2010), own calculations
Spain, China	6.3	5.1	9.9	NREL (2010), own calculations
Egypt	5.6	4.6	9.9	NREL (2010), own calculations
Solar field cost, EUR/sqm	211	155	155	NREL (2010), Trieb (2009), Estela (2010) own calcualtions
Solar field cost, EUR/kW$_{net}$				
US	1181	713	1338	own calculations
Spain, China	1318	795	1539	own calculations
Egypt	1181	713	1539	own calculations
Heat transfer fluid cycle, EUR/kW$_{net}$				
US	370	217	331	NREL (2010), Trieb (2009), Estela (2010) own calcualtions
Spain, China	412	241	379	NREL (2010), Trieb (2009), Estela (2010) own calcualtions
Egypt	370	217	379	NREL (2010), Trieb (2009), Estela (2010) own calcualtions
Civil work, EUR/kW$_{net}$				
US	123	63	93	NREL (2010), Trieb (2009), Estela (2010) own calcualtions
Spain, China	136	70	106	NREL (2010), Trieb (2009), Estela (2010) own calcualtions
Egypt	123	63	106	NREL (2010), Trieb (2009), Estela (2010) own calcualtions
Land costs, EUR/kW$_{net}$				
US	43	56	68	NREL (2010), own calculations
Spain, China	48	62	78	NREL (2010), own calculations
Egypt	43	56	78	NREL (2010), own calculations
Power block, EUR/kW$_{net}$	861	601	601	NREL (2010), own assumptions & calculations
6 h Thermal energy storage, EUR/kW$_{net}$			593	NREL (2010), Price et al. (2002), own assumptions & calculations
Engineering, construction management, commissioning[a]	3.8%	3.8%	3.8%	NREL (2010)
Project development fixed, million EUR	10	12	12	NREL (2010)
Project development variable[a]	1.0%	1.0%	1.0%	NREL (2010)
Engineering, procurement and construction (EPC), EBIT-margin	8.0%	8.0%	8.0%	own assumptions

a Share of direct investment costs (solar field, heat transfer fluid cycle, civil work, power block and thermal energy storage)

Table B.2: CSP parabolic trough – operations & maintenance costs, construction time, plant size and lifetime

	2010	2020, excl. storage	2020, incl. storage	Source
Operations & maintenance cost				
Share of investment cost p.a.	2.0%	2.0%	2.0%	European Commission (2007)
Inflation of O&M cost p.a.	2.1%	2.1%	2.1%	Eurostat (2010)
Construction time, months	24	24	24	own assumptions
Plant size, MW_{net}	50	300	300	own assumptions
Plant lifetime, years	25	25	25	EPIA (2010b)

Table B.3: CSP parabolic trough – solar-to-electric efficiency

	2010	2020, excl. storage	2020, incl. storage	Source
US	14.8%	19.0%	19.0%	NREL (2010), Ferrostaal (2009), own calculations
Spain	13.6%	17.5%	17.5%	NREL (2010), Ferrostaal (2009), own calculations
China	13.3%	16.5%	16.5%	NREL (2010), Ferrostaal (2009), own calculations
Egypt	15.2%	19.3%	19.3%	NREL (2010), Ferrostaal (2009), own calculations

Table B.4: Direct normal irradiation, kWh/sqm

	2010	2020, excl. storage	2020, incl. storage	Source
US (Daggett Barstow)	2723	2723	2723	U.S. DOE (2011), own calculations
Spain (Sevilla)	2090	2090	2090	U.S. DOE (2011), own calculations
China (Erenhot)	2222	2222	2222	U.S. DOE (2011), own calculations
Egypt (El Kharga)	2578	2578	2578	U.S. DOE (2011), own calculations

Appendix C

Table C.1: Natural gas and CO2 prices

	2010	2015	2020	2025	2030	2035	2040	2045	Source
Natural gas price, EUR/MWh$_{th}$									
US low case	11.2	19.3	24.5	30.2	35.4	40.6	46.5	53.2	IEA (2010d)
US high case	11.2	19.3	25.1	31.6	39.2	46.9	56.0	66.9	IEA (2010d)
Europe low case	19.5	28.7	32.5	36.4	41.1	46.0	51.5	57.7	IEA (2010d)
Europe high case	19.6	29.5	37.1	43.8	52.4	60.2	69.2	79.6	IEA (2010d)
CO2 price, EUR/ t CO_2									
High case	12.9	16.8	22.0	29.7	40.0	54.1	73.0	98.5	Bloomberg New Energy Finance (2011)
Low case	0	0	0	0	0	0	0	0	Own assumptions

Table C.2: Key parameters of CCGT power plant

	2010	2020	Source
Investment costs, EUR/kW$_{net}$ installed	700	700	European Commission (2008)
O&M cost excluding fuel, EUR/kW$_{net}$ installed p.a.	29	36	European Commission (2008)
System efficiency (lower heating value)	58%	61%	McKinsey & Company (2007)
Construction time, years	2	2	Own assumptions
Plant lifetime, years	25	25	Own assumptions

Appendix D

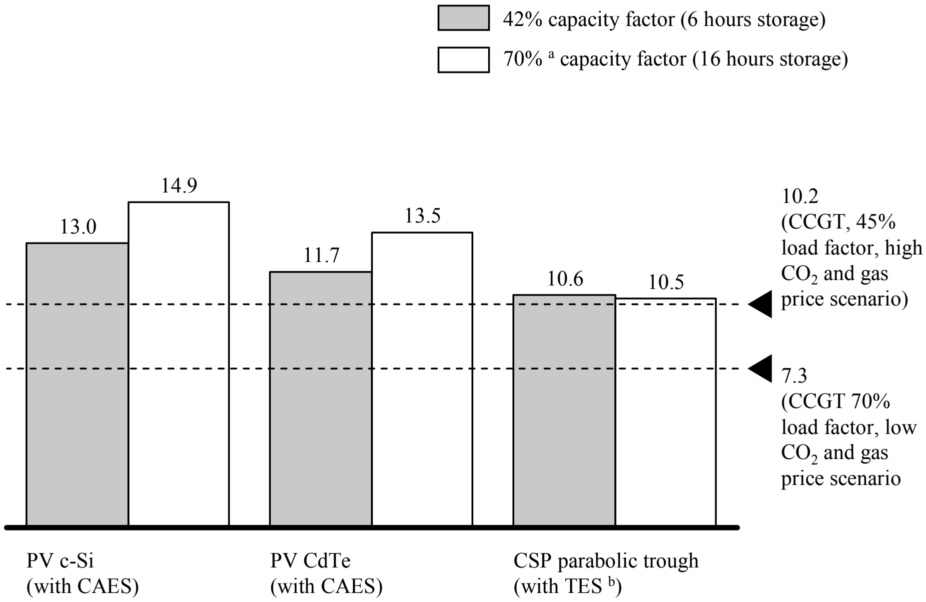
Table D.1: Nominal discount rates for PV and CSP power plants

	2010	2020	Source
US	8.0%	8.0%	Own assumptions
Spain	8.0%	8.0%	Own assumptions
China	12.6%	12.6%	(UNFCCC, 2010)
Egypt	14.1%	14.1%	(UNFCCC, 2010)

Table D.2: Inflation rate and USD/EUR exchange rate

	2010	2020	Source
Inflation rate, p.a.	2.1%	2.1%	Eurostat (2010)
USD/EUR exchange rate	1.40	1.40	own assumptions

Appendix E



a In Daggett (USA), baseload electricity (85% capacity factor) could only be reached with a very large solar field, which would lead to a signicant increase in LCOE. Only CSP plants closer to the equator with limited seasonal fluctuations and limited cloud cover could generate base load electricity (85% capacity factor) at no or limited additional LCOE.

b Thermal energy storage.

Figure E.1: Levelized cost of electricity in Daggett (USA), 2020, EUR_{2020} cents/kWh

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PAPER II

The Impact of Technology-push and Demand-pull Policies on Technical Change - Does the Locus of Policies Matter?

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Abstract

How to foster technical change is a highly relevant and intricate question in the arena of policymaking. Various studies have shown that technology-push and demand-pull policies induce innovation. However, there is a lack of work that distinguishes between the loci of policy support when assessing the policy-innovation relationship. We address this gap by shedding light on the question how the innovation effects of domestic and foreign demand-pull and technology-push policies differ. Using solar photovoltaics as a research case we conduct a panel analysis on 15 OECD countries over the period 1978 through 2005 with patent data. Three key findings emerged: First, our analyses suggest that domestic technology-push policies only foster innovative output within national borders. Second, both domestic and foreign demand-pull policies trigger innovative output in a country. Third, we find no indication that market growth induced by domestic demand-pull policies leads to more national innovative output than market growth induced by foreign demand-pull policies. Consequently, demand-pull policies create significant country-level innovation spillovers, which could disincentivize national policymakers to engage in domestic market creation. Based on these findings we discuss the need to establish supranational demand-pull policy schemes in order to address the spillover issue.

Keywords: technology-push; demand-pull; innovation spillovers; solar photovoltaics

1 Introduction

Society is facing serious problems such as climate change and resource depletion. To counter these challenges a "technology revolution" (Galiana and Green, 2009) in the field of clean technologies is required in order to decouple economic growth from adverse environmental impacts. Spurring technical change, i.e., the development and diffusion of new and/or improved technologies, is therefore pivotal. Yet in order to overcome market failures inherent in many environmental issues, policy support is crucial to foster technical change (Del Rio Gonzalez, 2009). This raises the question how public policies should be designed to deliver clean technology innovations (e.g., Mowery et al., 2010). Scholars widely agree that technical change is triggered by the supply side, i.e., progress in science, as well as by the demand-side. This dichotomy of technology-push and demand-pull has also been used to analyze the effect of policy on innovation (Rennings, 2000), and numerous studies have come to the conclusion that both policy types 'induce' innovation (e.g., Taylor et al., 2005).

However, thus far very few empirical studies have considered the locus of policy support when scrutinizing the impact of technology-push and demand-pull policies on innovation. Most scholars have focused on the effect of *domestic* policies while not accounting for a potential impact of *foreign* country-level policies on innovation in a country (e.g., Johnstone et al., 2009). Yet, a good understanding of country-level innovation spillovers – an effect that occurs when domestic innovation is triggered by foreign policies and vice versa - is crucial for policymakers, particularly when they invest public money in domestic policy schemes. Does innovation from domestic policy funding only accrue within the home country or do foreign industries also benefit? For example, in recent years German policymakers have invested several billion EUR annually into creating markets for photovoltaic technology, while the annual German public R&D funding in this field has remained below 50 million EUR. Subsequently, and in light of these large investments maybe not surprisingly, a heated debate has unfolded over whether this policy mix yields sufficient national innovative output and increases industry competitiveness or whether Germany is funding the 'learning curve of the world'.

The very limited number of studies that address the innovation effect of *foreign* policies have yielded inconclusive results. For demand-pull policies, Popp (2006) finds no evidence of country-level innovation spillovers in the case of air pollution control technologies. Opposed to that, Dechezleprêtre and Glachant (2011) investigate wind power and show spillovers from demand-pull policies, but – surprisingly – not from technology-push policies, although a positive effect could be expected with the general literature on R&D spillovers (Griliches, 1992).

To contribute to a clarification of these diverging findings, this paper distinguishes between different loci of policy support and addresses the question how the innovation effects of domestic and foreign demand-pull and technology-push policies differ. To do so, we use the case of solar photovoltaics (PV) and conduct a panel analysis with patent data of 15 OECD countries in the period 1978 through 2005.

The structure of this paper is as follows: In the subsequent section, we present our hypotheses on the innovation effects of different policy measures. In section 3 we provide details on the research case before we describe our methodology. Section 5 presents the results, which we discuss in section 6 before we conclude.

2 Policy-induced technical change: review and hypotheses

Two kinds of theories emerged in the 1950s and 1960s to explain technical change: "technology push" and "demand pull" (Dosi, 1982). The technology-push concept assumes a supply-side-driven and mainly linear process from research to development and ultimately to diffusion (Bush, 1945). In response to the advocates of technology-push, Schmookler (1966) formulated the demand-pull hypothesis, postulating that anticipated market demand was a key determinant of technical change by incentivizing research in new directions. The debate around the driving forces of technical change has reached a consensus that a combination of technology-push and demand-pull is necessary as they closely interact (Mowery and Rosenberg, 1979).

It has been widely recognized that for environmental innovations in particular, policy support is an important trigger (Kemp, 1997) for three main reasons. First, as most environmental technologies still require substantial R&D investments until reaching competitiveness, they suffer especially from knowledge spillovers (Rennings, 2000). Second, the uncertainty about future returns of environmental R&D investments is particularly high (Jaffe et al., 2002). Third, negative external effects inherent in most environmental issues put the relative competitiveness of environmental technologies at a disadvantage (e.g., Horbach, 2008). These problems can be addressed with technology-push and demand-pull policies: Technology-push policy is typically enacted as public R&D funding and, as such, can directly mitigate underinvestment in R&D. Demand-pull policies can be devised as market based instruments such as tradable permits, feed-in tariffs or command and control regulation inducing demand through standard setting (Jaffe et al., 2002). As a consequence, demand-pull policies can reduce the uncertainty of R&D investments through the creation of markets and can compensate for competitive disadvantage caused by negative external effects.

In the following sections, we derive two sets of hypotheses focusing on the innovation effects of I) technology-push policies, and II) demand-pull policies. For both policy determinants we evaluate how the effects of domestic and foreign policies differ.

2.1 Innovation effects of domestic and foreign technology-push policies

Thus far, a wide set of empirical studies has demonstrated a positive influence of domestic technology-push policies on innovative output. Examples include a study by Watanabe and colleagues (2000), who econometrically assess the effect of national public R&D funding on innovation in the Japanese PV sector and argue that this funding initiated a "virtuous cycle", creating innovation, price reductions, market growth, and additional industry R&D. Besides solar energy Johnstone and colleagues (2009) also evaluated the effect of public R&D funding on other renewable energy technologies using patent counts to measure innovative output. For three out of five technologies, their results indicate a positive effect of public R&D funding on innovation. In the field of sulphur dioxide ($S0_2$) abatement technologies, there are also indications that technology-push policy instruments have a positive impact on innovation (Taylor et al. 2005). Assessing wind energy innovation with a two factor learning curve model, Klaassen and colleagues (2005) also detect a positive effect of public R&D funding on innovation. These empirical findings are consistent with arguments to be found in the general literature on technical change: Technology-push has a positive effect on innovation as it broadens the scope of search and thus also exploits opportunities beyond existing avenues (Dosi 1988). Therefore we hypothesize:

H I a: The higher the domestic technology-push policy funding in a technological field, the higher a country's innovative output.

Interestingly, the vast majority of studies exclusively scrutinize the effect of *domestic* technology-push policies on innovation. Only very recently has the impact of foreign technology-push policies on a country's innovative output been analyzed in a study on wind energy. No positive innovation effect of such policies has been found (Dechezleprêtre et al 2011). It appears to be a sound assumption that governments award technology-push policy funding almost exclusively to domestic innovators in order to support the development of national industries. However, in contrast to these empirical findings, innovators might nevertheless benefit from foreign technology-push policy funding due to knowledge spillovers. It is widely recognized that knowledge spillovers exist on a national as well as an international level (Griliches, 1992; Grossman and Helpman, 1991). Building on this, we expect that the knowledge created through technology-push policies in a certain country will also partly spill over to other countries. Therefore, we postulate a positive innovation effect of foreign technology-push policies and test the following hypothesis:

H I b: The higher the foreign technology-push policy funding in a technological field, the higher a country's innovative output

Although spillovers exist on an international level, they primarily occur within a country (e.g., Jaffe et al 1993). In addition, as outlined above, domestic innovators are unlikely to benefit directly from foreign technology-push policy funding. In conclusion, despite a positive effect of growth in foreign technology-push policy funding on innovation in a country, we expect this effect to be weaker than in the case of domestic technology-push policies. We therefore hypothesize:

H I c: The growth in domestic technology-push policy funding triggers more innovative output in a country than the growth in foreign technology-push policy funding.

2.2 Innovation effects of domestic and foreign demand-pull policies

Scholars of environmental economics widely assume that demand-pull policies not only lead to diffusion but also induce innovation (Newell et al., 1999). Also, evolutionary approaches to policy suggest that governments should use demand-pull policies to create niche markets, which protect emerging technologies from competition with established designs (e.g., Kemp et al., 1998; Nill and Kemp, 2009). However, these literature streams mostly do not differentiate between the effect of domestic and foreign demand-pull policies. While various empirical studies find support for the 'inducement effect' of demand-pull policies, they mainly focus on the impact of domestic demand-pull policies on innovation in a country: For example, using patent data Popp (2003) shows that the adoption of the 1990 Clean Air Act in the US, which introduced tradable permits for sulfur dioxide emissions, positively affected US innovators in the field of pollution control. With a similar focus on sulfur dioxide emissions regulation in the US, Taylor and colleagues (2005) come to the conclusion that command and control as well as market-based demand-pull policies induce innovation as measured with US patent data. Brunnermeier and Cohen (2003) also find a positive impact of environmental regulation pressure, i.e., demand-pull policies, on innovation using panel data of 146 US manufacturing industries. Differentiating between a variety of policy instruments in the field of renewable energy technologies, Johnstone and colleagues (2009) present proof for the positive influence of domestic demand-pull policies on innovation in a country (e.g., in the case of investment incentives). Based on the extant literature, we suppose a positive relationship between domestic-demand-pull policies and innovation in a country.

H II a: The bigger the domestic market created by demand-pull policies in a technological field, the higher a country's innovative output.

Surprisingly, few scholars have thus far evaluated the effect of foreign demand-pull policies on innovation in a country. The results of these studies are mixed. Popp (2006) analyzes the innovation and diffusion effect of command and control policies in the field of air pollution control technologies. Based on patent data from Germany, Japan, and the United States, he concludes that innovators positively react to demand-pull policies in their own country yet not to demand-pull policies initiated abroad. In contrast, Lanjouw and Mody (1996) investigate command and control policies targeting vehicle emissions and present empirical evidence, also based on patent data, that innovation in a country can also be driven by policies abroad. A more recent article comes to a similar conclusion (Dechezleprêtre and Glachant, 2011).

The latter findings appear to be comprehensible given that a national market created by demand-pull policies is typically not completely shielded from foreign competitors and innovators. We therefore argue that both domestic and foreign demand-pull policies have an innovation effect in a country. We hypothesize:

H II b: The bigger the foreign market created by demand-pull policies in a technological field, the higher a country's innovative output.

The question remains whether the positive innovation effects of domestic and foreign demand-pull policies differ in strength. The literature stream on user-producer interaction helps address this question. User-producer interaction theory assumes that the development of new technologies requires a close interaction between the users and producers of a technology (Lundvall, 1985; Lundvall, 1988). This stream of literature implies that domestic demand is an important driver of innovation activity in a country, as local innovators are better informed about developments in their home markets due to regional and cultural proximity (Beise and Rammer, 2003).[1] For example, compared to foreign firms, domestic firms are likely to be more aware of local customer preferences and have superior access to customers. In addition, domestic users often help local innovators to scrutinize and further develop innovations (Fagerberg, 1995; Linder, 1961). This thinking has also influenced the literature on lead markets, which considers domestic demand as an important driver of innovation and ultimately global diffusion of innovation (Bartlett and Ghoshal, 1990; Beise, 2004).

In addition, the widely discussed Porter Hypothesis is helpful in deriving a hypothesis on the innovation effects' relative strength of domestic and foreign-demand pull policies (Porter, 1991; Porter and van der Linde, 1995). While in its 'weak' form the hypothesis suggests that market-based environmental regulation can have a positive effect on innovation in a country, its 'strong' version argues that the positive innovation effect can translate into a competitive advantage of firms in a country (Jaffe and Palmer, 1997). This implies that country-level innovation spillovers of environmental regulation are rather limited. This is because if such spillovers were substantial, it would be unlikely that domestic firms could maintain a competitive advantage over foreign firms. However, the Porter Hypothesis certainly does not claim universal validity and therefore calls for further theory building and empirical testing.

While the aforementioned literature does not preclude an innovation effect of foreign demand, it suggests that changes in domestic demand tend to have a stronger impact on innovation than foreign demand changes. This line of reasoning suggests that the innovation effects of domestic and foreign demand-side policy are also likely to differ in strength. It appears that innovators can more easily exploit domestic than foreign demand-pull policies for reasons of regional and cultural proximity. In conclusion, the above-mentioned literature suggests that market growth induced by domestic demand-pull policies presumably has a higher impact on innovation than market growth induced by foreign demand-pull policies. We therefore hypothesize:

H II c: *Domestic market growth created by demand-pull policies triggers more innovative output in a country than foreign market growth created by demand-pull policies.*

3 Research case

The case of solar PV is very well suited to test the above hypotheses for two reasons. First, electricity production with solar PV is still not competitive with fossil fuels and its diffusion will depend on adequate policy support for years to come (Bagnall and Boreland, 2008). Consequently, PV has been exposed to both technology-push and demand-pull policies in the past in a variety of countries (IEA, 2004). Second, patenting activity, an important indicator of innovative output, has been dynamic over the last decades (see Figure 1), and costs of solar PV have decreased considerably.

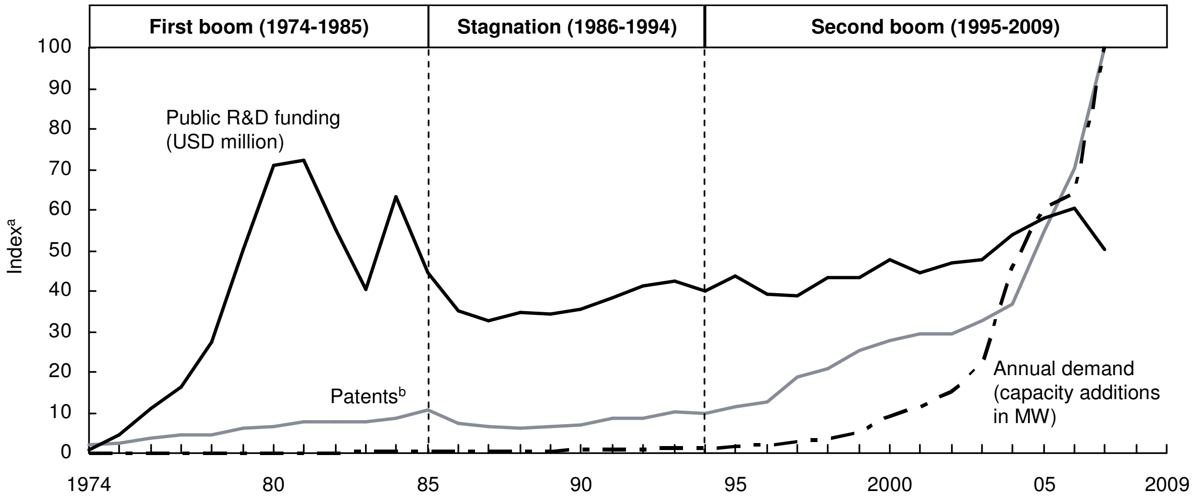
Below we first provide context on the evolution of our key variables since 1974: Policy support and innovative output in PV. We then briefly outline how the PV industry developed in order to illustrate how demand-pull policies have contributed to an increasing globalization of innovation and value creation.

3.1 Development of innovative output and policy support

The development of PV followed the pattern of double-boom cycles (Schmoch, 2007) and can be subdivided into three phases based on technological activity: 1) First boom 2) Stagnation 3) Second boom (Figure 1). Following (Schmoch, 2007), we proxy technological activity with patent counts and define the end of the first boom as the first temporary maximum of patent counts. In the stagnation phase thereafter, patent activity describes a trough. The start of the second boom is then indicated by a take-off in patent activity in 1995.

3.1.1 First boom (1974-1985)

Soon after the patenting of the first solar cell in 1954 (Goetzberger et al., 1994) PV emerged as an option for electricity generation. However, in the 1960s very high cost kept the technology mostly to the realm of space applications. Triggered by the two oil price shocks in the 1970s, particularly, the US, German, and Japanese governments significantly increased public R&D funding for PV (IEA, 2004, 2010). Demand-pull policies in contrast to public R&D funding played a minor role in this phase and cumulative installed PV capacity remained well below 100 MW until 1985. At the same time, innovation dynamics in PV intensified: Annual patent activity increased significantly by 16% p.a. between 1974 and 1985. In addition to the leading PV design crystalline silicon, a variety of pre-commercial designs emerged in the 1970s and early 1980s, including thin film approaches and high efficiency solar cells. These pre-commercial designs did not yet offer a levelized cost of electricity sufficient to compete in the market with crystalline silicon. However, their value mainly lay in the option to become the highest- performing design in the future through further innovation.



a Patents and annual demand indexed to 100 in 2007; Public R&D funding indexed to 50 in 2007 for graphical representation purposes
b Based on inventor country counts and „claimed priorities"

Figure 1: Development of patents, public R&D funding, and annual demand in PV (15 OECD countries with highest PV patenting activity); Sources: Bubenzer and Luther (2003), Eglash (2007), EPIA (1996, 2001), IEA (2004, 2010), IEA-PVPS (2009), INPAFAMDB, the global patent family database of The Scientific & Technical Information Network (STN).

3.1.2 Stagnation (1986-1994)

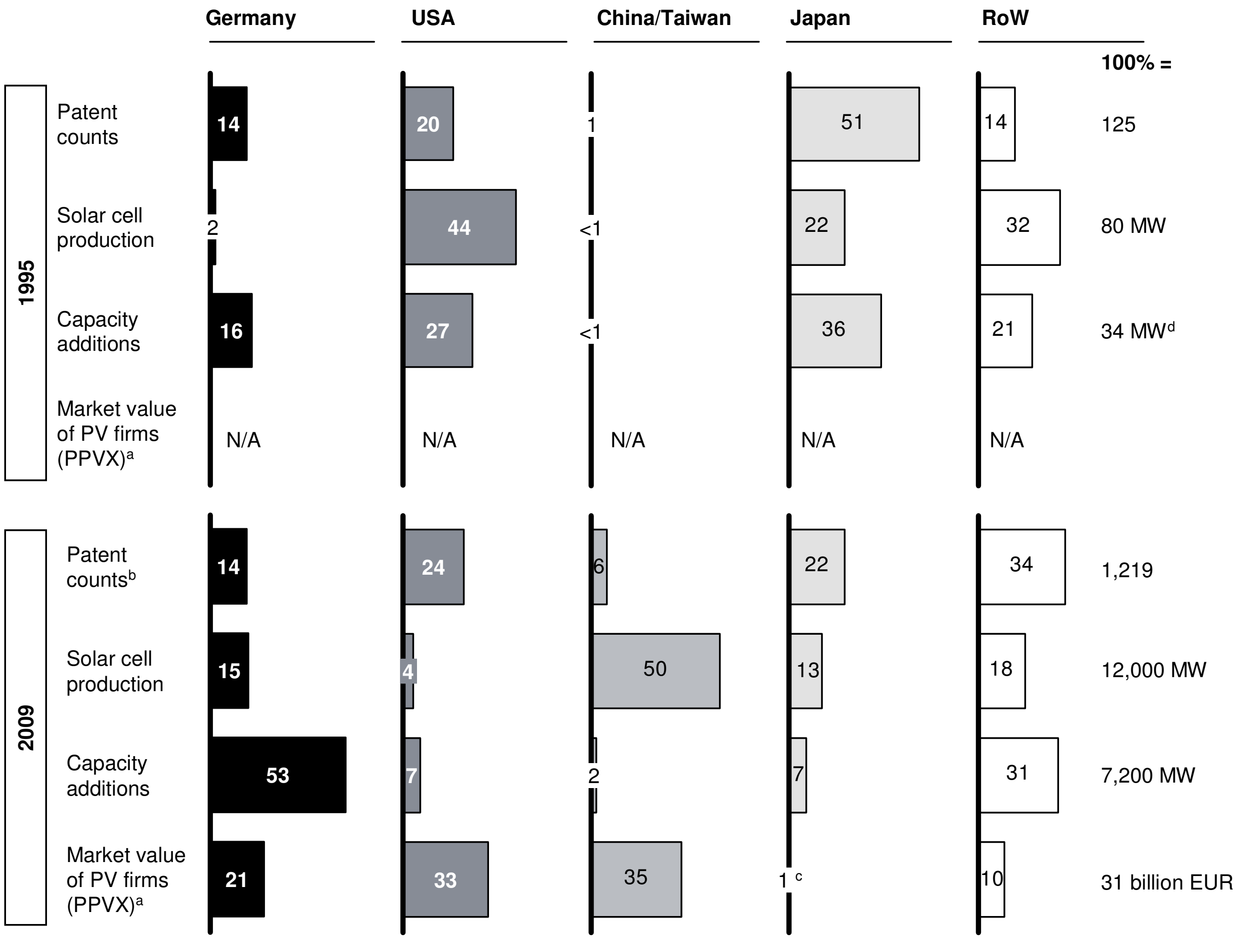
In the second phase, public R&D funding as well as patent activity stagnated (Figure 1). US and German policymakers were especially disillusioned as cost targets set out in the early 1970s were missed by an order of magnitude (Kazmerski, 1997). In addition, decreasing oil prices reduced the search efforts for alternative energy forms. This resulted in low R&D funding levels: By 1987 the funding had dropped to 50% of the peak reached in 1981 and only slowly recovered to values similar to those in 1985 (IEA, 2010). Demand, still from a low base, continued to grow at an average yearly rate of 16%. It was driven by demand-pull policies such as the German federal feed-in law established in 1991. In 1994 cumulative global PV installations reached roughly 500 MW. At the same time, innovation activities slowed down. Patent activity decreased by more than 40% between 1985 and 1988, roughly reaching its 1985 level again only in 1994. While technological variety among pre-commercial designs remained high, amorphous silicon reached market shares of up to 30% in the late 1980s, reaching competitiveness with crystalline silicon. However, eventually amorphous silicon missed the aspired cost targets and its share declined again to less than 10% until the mid 1990s.

3.1.3 Second boom (1995-2009)

Since 1995 annual PV demand developed very dynamically, induced by demand-pull policies as several countries launched demand-pull policy schemes such as investment subsidies and feed-in tariffs (IEA, 2004; Jäger-Waldau, 2007). Growth of the PV market accelerated significantly to an average of 41% p.a., reaching a cumulative installed capacity of around 23,000 MW in 2009 (EPIA, 2010). Conversely, R&D funding increased only slightly. Along with the growing PV market innovative output also increased: Patent activity increased substantially by on average 16% p.a. (Figure 1). Technological variety grew even further as organic and dye-sensitized solar cells emerged, crystalline silicon, however, remained the leading design with market shares of around 90% (Photon 2010).

3.2 Evolution of the PV industry during the second boom phase

Prior to the second boom phase, the PV industry was still in its infancy due to very limited market volumes. In the course of the second boom phase, however, the global PV market grew by several orders of magnitude (EPIA, 2010) and PV became a multibillion EUR industry. In this phase, the structure of value creation in the global PV industry also changed significantly (Figure 2): Germany became the largest market for PV installations, the US took the lead in terms of innovative activity, China/Taiwan emerged as the major production hub for solar cells, and Japan lost its leading position in the industry.



a Photon Photovoltaics Stock Index; average market capitalization Jan-Jun 2010; mainly solar cell/module manufacturers
b As of 2007, data for 2009 not yet available
c Japanese PV industry largely consists of business units belonging to industry conglomerates. Therefore only one Japanese firm is listed in the PPVX
d IEA countries only

Figure 2: Value creation in global PV industry in 1995 and 2009, percent; Source: EPIA (2010), IEA-PVPS (2009), Photon (2010), Watanabe et al. (2000); Bloomberg, INPAFAMDB, the global patent family database of The Scientific & Technical Information Network (STN).

While Germany had already engaged in domestic demand-pull policy support prior to 2000, the introduction of a feed-in tariff within the framework of the Renewable Energy Sources Act led to a significant increase in funding levels. As a result, newly installed capacity in Germany represented over half of the world market in 2009. In global comparison, however, the German PV industry did not gain a higher share of patents. Similarly, while Germany's total production of solar cells and its share in the world market increased until 2009, its market share of cell production (15%) is much below its dominating share of capacity additions (53%).

Increasing shares of the US in global patenting activities and the high market value of US-based PV firms in 2009 contrast starkly with its strongly decreasing share of worldwide capacity additions. While US patent activity increased by a factor of 8 between 1995 and 2006 and more than factor 11 by 2007, public R&D funding remained rather stable until 2007 when via the Solar American Initiative higher public R&D budgets were allocated to PV (Eglash, 2007). Booming PV markets in Europe may also have incentivized innovative activity in the US. In addition, the dynamics of the European markets allowed US solar cell manufacturers to grow significantly[2], thus contributing to their market value.

Similar to the US firms, Chinese and Taiwanese PV firms also flourished, although hardly any PV capacity had been installed in these markets until 2009. However, in contrast to the US, China and Taiwan have become a major manufacturing location for largely domestic solar cell manufacturers (Photon, 2010). Patent activity also increased considerably since 1995 and the success of Chinese/Taiwanese firms is reflected in their high market value. As in the case of the US, it seems that demand-pull policy support in Europe has driven innovation and value creation in general in China and Taiwan.

While in 1995 Japan was the clear leader in the global PV industry, its position has eroded in recent years. Due to limited demand-pull policy support, PV capacity additions have stagnated since 2003 (IEA-PVPS, 2009). The production volume growth of Japanese solar cell manufacturers was also significantly below the market average between 1995 and 2009. In addition, Japan lost its lead in PV innovations in terms of patent counts to the US.

4 Methodology

In the following we provide details on the panel analysis that we used to statistically test our hypotheses. We first illustrate how we measured the dependent variable "innovative output" based on patent counts. Then we explain how we operationalized the independent variables and, lastly, specify a negative binomial model to estimate coefficients.

4.1 Measuring innovative output

Despite some clear limitations, patents are widely accepted as a measure of innovative output (Griliches, 1990; Jaffe, 1986; Schmookler, 1966).[3] Therefore, we use counts for solar PV patents on a panel of 15 OECD inventor countries[4] to measure innovative output on a national level. Our sample accounts for more than 90% of all global solar PV patent counts in this period based on inventor country. The technology scope of our patent data set comprises the core of photovoltaic electricity generation, i.e., all patents that directly relate to PV cell or PV module inventions in all types of PV technologies. International patent classifications (IPC) were used to compile the data. We identified relevant IPCs based on a literature research (Dechezleprêtre et al., 2008; Johnstone et al., 2009), a key word search in the IPC catalogue and based on advice from two experienced

[2] In 2009 less than 5% of global solar cell volume was produced in the US as leading US solar cell manufacturers significantly shifted their production to Malaysia and the Philippines.
[3] The fact that not all innovations are patented is the most serious limitation (Hall et al., 2005). However, one can reasonably assume that patent counts are positively correlated to the quantity of non-patented innovations and stand for the level of the corresponding technology activities (Schmoch, 1997).
[4] Australia, Austria, Belgium, Canada, France, Germany, Great Britain, Italy, Japan, Netherlands, South Korea, Spain, Sweden, Switzerland, US.

patent researchers.[5] In addition, two of the authors independently assessed the relevance of the selected IPCs by analyzing patent title and abstract of random subsamples and excluded classes with low relevance scores. The patent data set was extracted from the global patent family database of The Scientific & Technical Information Network (STN), INPAFAMDB[6]. We counted patent families instead of singular patents (publications) as one patent family typically corresponds to one invention. Whole patent counts[7] based on inventor country were used to measure the innovative output of the 15 sample countries (OECD, 2009).

A challenge in using patent counts as a measure of innovative output is that most patents only have very limited commercial value and thus hardly qualify as innovative output. Harhoff and colleagues (2003) for example showed for a set of German patents that the 25% most valuable patents account for more than 90% of patent value. In order to prevent diluting our measure of innovative output with purely inventive output we use patent family size as a value criterion. Harhoff and colleagues (2003: 1343) have shown that "large international patent families are particularly valuable". We therefore use two alternative operationalizations to increase the robustness of our analyses: 'claimed priorities' – patent families with publications in at least two countries – and 'triadic patents'[8] as dependent variables (Frietsch and Schmoch, 2010; Sternitzke, 2009).[9] Claimed patents and triadic patents account for 45% and 24% of the total patent counts in our sample.[10] Moreover, claimed and triadic patents almost always offer information about the inventor country, while this information is mostly not available in the case of patents with a publication in just one country (singular patent).

To determine at what point in time an innovation occurred, we used the first filing of a patent worldwide (priority date) as it tends to be closest to the actual inventive activity (Harhoff et al., 2003; OECD, 2009; Schmoch, 2007). A potential bias within patent data is caused by truncation. After the application it takes about 18 months until all patents are published. Then some

[5] H01L-031/042...058 and H01L-027/142.

[6] INPAFAMDB (the International Patent Family Database) is a bibliographic patent family database which covers the full spectrum of patent technologies for 95 issuing authorities, dating from the early 1800s. The database features a one-record-per-patent-family file design. Further information can be found under http://www.stn-international.de/dif_inpafam.html.

[7] Whole counts attribute full credit to each inventor country involved in the creation of a single invention. Scholars have shown that whole and fractional counts yield very similar results (Narin and Breitzman 1995).

[8] Patent families with publications in at least Germany or the European Patent Office, Japan or China, and the US.

[9] One could argue that an inventor, who files a patent in several countries, does so because of existing or expected demand in these countries. Hence, the existence of a claimed patent already implies that the underlying invention might have been influenced by foreign demand. If we assume that we exclude a certain – most likely small – amount of innovative output by restricting our measure to claimed or triadic patents, this could indeed bias the effect of foreign demand-pull policies on innovative output. To assure that this potential bias does not distort our results, we use total patent counts based on priority country first as a third operationalization of innovative output (See Table B.1 in the Appendix). Priority country first is used as a proxy for inventor country as the latter information is mostly not available for singular patents. Primarily in the case of small countries (e.g., Switzerland), this can create biases as inventors in small countries tend to file their patents in patent offices of larger neighbouring countries (e.g., Germany).

[10] These numbers exclude Japan, whose propensity to patenting is significantly higher than that of other countries. For the Japanese case the share of claimed patents (triadic patents) amounts to 9% (5%).

patents require additional time until they become claimed or triade patents. By restricting our panel to the period 1978-2005, we assured that our patent data do not suffer from a truncation bias.[11] In total our data set comprises 4,604 claimed patent counts and 2,445 triadic patent counts between 1978 and 2005.

4.2 Measuring determinants of innovation

4.2.1 Demand-pull policies

The heterogeneity of demand-pull policy features across nations with respect to level, duration, degression, and other features (IEA, 2004) makes it very difficult to even crudely operationalize demand-pull policies on an instrument level as independent variables. Therefore, we measured demand-pull policies on an aggregated level using domestic as well as foreign PV capacity additions[12] as proxies (Klaassen et al., 2005). In line with Dechezleprêtre and Glachant's (2011) study on wind power, we assume that capacity additions have been policy induced so far in the field of PV since grid connected PV capacity yields levelized costs of electricity which are still considerably above wholesale electricity prices.[13]

For each of the 15 OECD sample countries we extracted PV capacity additions from national survey reports of the IEA (IEA-PVPS, 2009) and other sources (EIA, 2000; Jacobsson et al., 2004; OECD, 2011). To approximate foreign capacity additions we assumed that the world market can be represented by the total installations in the 15 sample countries, which accounted for about 80% of the cumulative installed PV capacity in 2005. For each country we furthermore split foreign into continental capacity additions (excluding domestic additions) and intercontinental capacity additions to control for geographic proximity of demand.

We also tested the influence of potentially anticipated capacity additions in future periods t + 1 and t + 2 as well as market growth rates. These determinants were excluded from further analyses, however, as they turned out to have little or no explanatory value.

4.2.2 Technology-push policies

In line with other studies we used public R&D funding in the field of PV to measure technology-push policies (e.g., Johnstone et al., 2009). Analogously to the demand-pull policy variables we specify three variables: domestic, continental and intercontinental public R&D funding. Data are

[11] This threshold was selected by comparing the share of claimed and triade patents in the data set at two different points in time. To do so we generated the patent data set twice: in February 2010 and December 2010. In between these two points in time the share of claimed and triade patents only increased marginally for the priority year 2005.

[12] While typically volume is used to measure the effect of demand-pull policies on innovation (e.g., Klaassen et al., 2005), we also specified a model using monetary demand (i.e., the amount of demand-pull policy funding) as a driver of innovative output. However, model results changed only marginally.

[13] Indeed one could argue that market growth is not purely determined by demand-pull policies but also depends on the supply side. While this is true in the short term, most policymakers regularly adapt demand-pull policies (e.g., in an annual cycle) to reflect changes on the supply side. Moreover policymakers usually pursue a diffusion goal for PV and other types of renewable electricity. Therefore annual market growth appears to be an adequate proxy for demand-pull policies.

taken from the International Energy Agency's "Energy technology research and development" database (IEA, 2010).[14] Funding levels are expressed in USD 2008 prices and power purchasing parity (PPP). Apart from these R&D values, we tested several additional potential determinants in order to increase the robustness of our analysis: First, we included the cumulative R&D funding of the past 5 years in our models. Second we lagged R&D variables by 1, 3, and 5 years, assuming a time lag between the R&D investment and patent applications (Hausman et al., 1984; Jaumotte and Pain, 2005). However, we abandoned cumulative as well as lagged R&D values based on initial model results. Several authors back these findings (e.g., Brunnermeier and Cohen, 2003; Hall et al., 1986) and argue that there is no substantial lag between R&D and patent applications.[15] In addition, we tried an alternative functional form of the R&D variables ($R\&D^2$). However, since this led to a deterioration of the model fit we did not include this functional form in our final models.

4.2.3 Control variables

In addition to policy support, changes in relative prices for input factors or substitutes can also create demand-pull (Hicks, 1932). Therefore we included the crude oil price in our models, the most important price signal in the energy sector which directly influences prices of inputs needed for electricity generation such as natural gas and coal. Oil price data are taken from the US Energy Information Administration's "Annual energy outlook" (EIA, 2009) using the 2008 price level.

We controlled for time effects by including a trend variable by which the three development phases of solar PV outlined in section 3 were assigned the values 0 – 2.[16] In addition, unobserved country-level heterogeneity is controlled for by using a model with country-fixed effects. Table 1 exhibits descriptive statistics for the independent variables, determinants and control variables.

Other studies have also found that technological opportunity is a determinant of innovation (e.g., Astebro and Dahlin, 2005). We refrained from including a technological opportunity variable in our models for two reasons. First, the innovative activity in the field of solar PV was and is largely policy driven since the technology will not become competitive any time soon (Bagnall and Boreland, 2008). Second, there are still significant potentials for advancing solar PV technology (Peters et al., 2011). Therefore, in the case of solar PV, variations in technological opportunity over time do not seem to be a major influencing factor of innovation.[17]

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[14] 10 data points supplemented with other sources (Bubenzer and Luther, 2003; Photon, 2009).

[15] In case of continental and intercontinental public R&D funding a time lag is more likely since spillovers typically occur with a time lag. But also in these cases lagging R&D values did not improve the model results.

[16] We also specified alternative models including the application year as a time trend. While the results are very similar to the ones presented in this paper, we decided to reject these models due to high multicollinearity. Depending on the model specification VIFs ranged between 13 and 14. The Pearson correlation coefficient for the time trend and continental capacity additions is 0.78. Bivariate correlation of the time trend and intercontinental capacity additions amounts to 0.948.

[17] Commonly, the discounted stock of previously filed patents reflecting the knowledge stock is also included in patent count models. Including a knowledge stock variable with a typical discount factor of 10%, our models yielded robust results. However, we opted for excluding such variables in our final model specifications, as the variance inflation factor by far exceeded an acceptable level. Kuttner (2004) suggests

Table 1: Descriptive statistics for model variables, period 1978-2005

	Unit	N	Mean	Min	Max	StDev.	Sum
Dependent variables							
Claimed patents	[-]	420	10.96	0	201	25.48	4,604
Triadic patents	[-]	420	5.82	0	125	13.81	2,445
All patents	[-]	420	62.66	0	1,245	202.67	26,317
Determinants							
Domestic public R&D funding	[m USD]	374	21.61	0	340.28	38.69	8,081
Continental public R&D funding (excluding domestic)	[m USD]	420	76.32	0	340.28	51.23	32,056
Intercontinental public R&D funding	[m USD]	420	193.05	25.58	456.79	70.06	81,083
Domestic capacity additions	[MW/a]	420	9.94	0	892.00	59.21	4,176
Continental capacity additions (excluding domestic)	[MW/a]	420	51.05	0	942.90	164.10	21,440
Intercontinental capacity additions	[MW/a]	420	88.14	0	1343.00	185.48	37,019
Control variables							
Crude oil price	[USD/Barrel]	420	40.47	15.97	88.69	19.84	16,998
Trend variable	[-]	420	1.11	0	2	0.82	466

Note: To improve readability, all values are displayed here as non-logged although some of them are logged in the model estimations.

4.3 Specification of regression model

The Poisson and the negative binomial model are common approaches to regress count data variables (Hausman et al., 1984). Since our data are overdispersed (see Table 1) we chose the negative binomial model. We used log values for all independent variables relating to public R&D funding or capacity additions. Since we detected autocorrelation and heteroskedasticity in our models, we chose heteroskedasticity- and autocorrelation consistent- (HAC) standard errors.

A particular concern when using domestic public R&D funding as a predictor for patent counts is endogeneity. Patenting activity could be a decision criterion for governments when allocating public R&D funding to institutions.[18] Therefore patent counts and domestic public R&D funding might simultaneously cause each other. To address this concern, we conducted a test for endogeneity (Brynjolfsson et al., 2011). However, the result of this analysis fails to reject the null hypothesis that the variable public R&D funding is exogenous (see Appendix A for details).

avoiding a variance inflation factor (VIF) above 10. Depending on the model specification, the VIF of the knowledge stock variable ranged between 21 and 40.

[18] Since governments typically allocate public R&D funding to domestic innovators, the variables continental public R&D funding and intercontinental public R&D funding are not exposed to a potential endogeneity issue.

5 Results

To robustly test hypotheses H I a,b and H II a,b we detail the dependent variable and the determinants in our model specifications as follows: Regarding the former, we use two different measures of innovative output, claimed and triadic patent counts. While we think these two variables are appropriate proxies for innovative output we also specify models based on all patent counts to assure the robustness of our analysis. Regarding the determinants, we include a differentiated set of policy variables to distinguish between the innovation effect of domestic and foreign policies. Public R&D funding as well as capacity additions are both split up in three geographical components (domestic, continental and intercontinental). Since the intercontinental capacity variable features a relatively high correlation with the time trend and the continental capacity variables (see correlation matrix in Appendix Table B.2), we, in addition, specify models which only comprise domestic and continental variables.

In sum, we now present the results of four models. In model A we regress domestic and continental public R&D funding as well as domestic and continental capacity additions on claimed priorities. In model B we then add intercontinental public R&D funding and intercontinental capacity additions. Models A and B are replicated for triadic patents as a dependent variable (models C and D) and for 'all patents' as a dependent variable (see models E and F in Table B.1 in the Appendix).

Table 2: Estimated coefficients of the negative binomial fixed effects model for 15 OECD countries 1978 – 2005, claimed patents and triadic patents

	Model A	**Model B**	**Model C**	**Model D**
Dependent variable	**Claimed patents**	**Claimed patents**	**Triadic patents**	**Triadic patents**
Domestic R&D funding	0.307*** (0.065)	0.322*** (0.070)	0.326***(0.076)	0.332*** (0.084)
Continental R&D funding (excl. domestic)	-0.053 (0.053)	-0.064 (0.065)	-0.058 (0.069)	-0.076 (0.088)
Intercontinental R&D funding	--	0.197 (0.145)	--	0.132 (0.152)
Domestic capacity	0.163*** (0.030)	0.128*** (0.032)	0.217*** (0.036)	0.188*** (0.042)
Continental capacity (excl. domestic)	0.206*** (0.032)	0.160*** (0.034)	0.204*** (0.038)	0.170*** (0.044)
Intercontinental capacity	--	0.093* (0.041)	--	0.083 (0.057)
Crude oil price	0.009**(0.003)	0.006† (0.003)	0.010** (0.003)	0.008* (0.004)
Time trend	0.349** (0.115)	0.194† (0.114)	0.263* (0.126)	0.125 (0.119)
Country fixed effects	Yes	Yes	Yes	Yes
Intercept	-1.298*** (0.318)	-2.104* (0.909)	-1.915*** (0.423)	-2.414* (1.001)
AIC:	1592	1583	1304	1303
Mean number of patents:	10.96	10.96	5.82	5.82
Fitted mean:	12.18	12.11	6.40	6.40

Notes: Heteroskedasticity and autocorrelation consistent errors in parentheses (full period, N=374);† $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Estimated coefficients of the regression models A – D are provided in Table 2. The positive coefficients at the 0.1% significance level of the variable domestic R&D funding in all models suggest a positive effect of domestic technology-push policies on innovative output. Hence we find clear support for hypothesis I a. However, our results suggest that domestic innovators do not benefit from publicly funded research and development abroad since neither continental nor intercontinental public R&D funding has an effect on innovative output in a country. Hence, we do not find support for hypothesis I b. Consequently, domestic public R&D funding has a stronger impact on innovation in a country than foreign public R&D funding. This is in line with hypothesis I c.

Furthermore, the coefficients of domestic and continental capacity variables are positive at the 0.1% significance level in all models A-D. In addition, model B also yields a positive coefficient at the 5% significance level for the intercontinental capacity variable. While these findings underscore the positive innovation effect of domestic demand-pull policies shown in many prior studies, they also indicate the necessity to consider foreign demand-pull policies as a determinant of innovative output. It appears that the access of foreign innovators to national policy-induced markets causes country-level innovation spillovers. However, the positive influence of the continental capacity variables is clearer than in the case of the intercontinental capacity variables. This could hint at decreasing country-level innovation spillovers of demand-pull policies as geographic distance increases. The positive effects of domestic and foreign demand-pull policies on innovative output clearly support our hypotheses II a and II b. When using all patent counts as a dependent variable the results are very similar: the outcome for hypotheses I a, b, c and H II b is identical, only for hypothesis II a results are not fully consistent (see Table B.1 in the Appendix).

Regarding control variables, all models in Table 2 indicate that as expected the crude oil price has a positive effect on innovative output – though in model B only at the 10% significance level –. All models but D suggest at least a weakly significant positive time trend.

In order to examine hypothesis II c, we compare the coefficients of the domestic and the continental capacity variables using a one tailed t-test (models A, C and D). In model B both continental and intercontinental capacities have a significantly positive influence on innovative output. To still compare the aggregate innovation effect of foreign markets with the one in domestic markets we ran this model again using foreign capacity as a determinant instead of separated continental and intercontinental capacity. If the coefficient of the domestic capacity variable (β_{Dom}) is significantly higher than the coefficient of the continental (β_{Cont}) or the foreign capacity variable (β_{For}), a one percent increase of the domestic market would trigger more innovative output in a country than a one percent increase of capacity abroad. This would imply that market growth induced by domestic demand-pull policies would have a stronger impact on innovative output than market growth abroad. Hypothesis II c would then be supported.[19] At first sight it might seem that countries with a marginal share of the world market are per se rather driven by foreign than by domestic markets. However, the theoretical concepts presented in section 2 suggest that a limited domestic market size makes it far more difficult to access foreign markets.

The results in Table 3 clearly indicate that across all models the null hypothesis is rejected. Therefore, our results do not support hypothesis II c. For model A2 we even find that β_{For} is greater than β_{Dom} at the 5% level. In this case market growth abroad seems to have a stronger impact on innovative output in a country than domestic market growth. These results further underline the explanatory value of foreign demand-pull policies for innovative output in a country. Conversely, this implies that substantial country-level innovation spillovers of demand-pull policies exist.

[19] At first sight it might seem that countries with a marginal share of the world market are per se rather driven by foreign than by domestic markets. However, the theoretical concepts presented in section 2 suggest that a limited domestic market size makes it far more difficult to access foreign markets.

Table 3: Results of a one tailed t-test for coefficients of capacity variables (hypothesis test H II c)

	Model A	Model B	Model C	Model D
Dependent variable	**Claimed patents**	**Claimed patents**	**Triadic patents**	**Triadic patents**
Null: $\beta_{Dom} > \beta_{Cont}$	-1.109 (0.134)	--	0.252 (0.599)	0.364 (0.642)
Null: $\beta_{Dom} > \beta_{For}$	--	-1.911 (0.028)	--	--

Notes: p-values in brackets; † p >0.90; * p >0.95; ** p > 0.99; *** p > 0.999

6 Discussion

The results of this study underscore that technology-push as well as demand-pull policies are key drivers of innovative output in the field of PV technology. Therefore, policymakers are in a position to decide over the success or failure of a technology that has the potential to be a cornerstone in the battle against climate change and resource depletion. In the following we discuss key implications of our findings for theory and policymakers.

6.1 Theory implications

According to our panel analysis, domestic and foreign demand-pull policies both have a clearly positive effect on innovative output in a country. Policy-induced market growth abroad apparently has at least the same innovation effect in a country as domestic market growth triggered by demand-pull policies. Thus, there is ample evidence for substantial country-level innovation spillovers in the case of demand-pull policies. In contrast, such spillovers do not seem to occur in the case of technology-push policies. Our results indicate that domestic public R&D funding only spurs an innovation effect within national borders. Below, we discuss how and why our findings – particularly regarding the innovation effect of demand-pull policies– deviate from the literature presented in section 2 and highlight technology characteristics that might explain this.

The findings of our analysis - focused on the single technology solar PV - interestingly are not fully consistent with the conclusions we would draw from the Porter Hypothesis as well as the literature on user-producer interaction. In the following we explore four possible explanations for this deviation, which might help to generalize our findings for certain other technologies. First, due to the high modularity of PV installations and low shipping costs of PV cells and modules, the exploitation of comparative cost advantages in specific geographies such as Asia is an attractive option for most PV cell/module manufacturers. In addition to production, innovative activities such as learning by doing and, to a certain extent, R&D also shift to Asia. Second, user feedback might only have limited value for producers as the share of operations and maintenance expenses – a cost position most benefitting from user feedback – is very low in the case of solar PV. Third, the link between producer and user has been rather weak in the PV industry in the past due to a highly fragmented user structure. Small-scale applications accounted for the majority of installed capacity. Hence the collection of user feedback is accompanied by high transaction costs, and the advantage of having an R&D department close to the user is limited. Fourth, some countries might not sufficiently capitalize on their demand-pull policies due to their innovation system characteristics. For example, while expertise in semiconductor technologies is beneficial to setting up a successful PV industry, this has not traditionally been a focus of technological development in Germany. In contrast, China and Taiwan have become leaders in the field of semiconductor manufacturing and leverage this knowledge for PV module production.[20]

A discussion of these deviations could prove fruitful for future theory building. In particular a more explicit and granular consideration of technology characteristics in future research on policy impacts on innovative output seems to be important in this context.

6.2 Policy implications

Our findings also have important implications for policymaking. We first discuss why this is the case. Second we present implications from the perspective of a national policymaker before we lastly address implications in a global context.

While policymakers can be confident that exclusively national innovators benefit from innovation effects of technology-push policies, this does not necessarily hold for demand-pull policies: In addition to domestic industries, foreign industries also benefit from national demand-pull policies. Certainly domestic demand-pull policies create national benefits beyond innovative output such as a contribution to fulfilling greenhouse gas emission targets and changes in the structure of power generation and distribution which is likely to be needed in the longer term. However, it is questionable whether policymakers will continue to invest in demand-pull policies if such policies cause country-level innovation spillovers that potentially undermine the competitive position of the national industry. Such spillovers are particularly disadvantageous when technologies are still far from competitiveness, as with PV (Bagnall and Boreland, 2008), since such technologies require a relatively high investment per unit of market created. For example, in Germany the committed feed-in tariff payments for capacity built by 2010 are likely to exceed EUR 50 billion (Frondel et al., 2008). If German policymakers realize that this investment does not sufficiently translate into innovative output, which can subsequently translate into national competitive advantage and employment, significant cuts in feed-in tariffs are likely. The resulting implications depend on whether the policymaker chooses a national or a global perspective.

From a national standpoint, policymakers should rather carefully invest in demand-pull policies such as feed-in tariffs in order to prevent country-level innovation spillovers. Such spillovers could be costly to a country's society or at worst undermine a country's competitive

[20] In 1995 and 2009 only one German company was among the top 20 semiconductor companies by sales (excluding pure play manufacturing companies) in the world (Source: iSuppli and Gartner Dataquest Corporation industry rankings). In 2009 four Chinese and four Taiwanese firms were among the top 15 pure play semiconductor manufacturing companies by sales worldwide (Source: IC insights, company reports).

position. Technology-push policies appear to be very well suited to complement demand-pull policy funding. They foster innovation and potentially improve the national competitive advantage. Possibly, increased investments in technology-push policies could even reduce the amount of spillovers on the demand-pull funding side: First a country improves its competitive advantage with the help of technology-push policies. Then it intensifies demand-pull policy funding. Now innovation spillovers will be lower as the more competitive domestic industry will capture a higher share of demand-pull policy funding and its innovation benefits.

From a global perspective, there is a considerable danger that national policymakers do not sufficiently invest in demand-pull policies to ensure continuous and predictable global market growth due to innovation spillovers of demand-pull policies. A prisoner's dilemma looms as in the case of global climate policy. For example, if German policymakers drastically reduced their support for PV and other countries did not significantly step up their efforts in a predictable manner due to fear of innovation spillovers, a market downturn would result. However, continuous global market growth is indispensable in order to tap into the enormous potential of solar PV power in the longer term: It maintains investor interest, reduces the cost of PV technology, and contributes to changes in the structure of the power generation and distribution needed to establish a power sector largely based on renewable energy. Consequently, national policymakers could forge a supranational demand-pull policy scheme which balances the effects of innovation spillovers and thus eliminates disincentives for the creation of demand-pull policies. In addition, such a "global PV deal" could efficiently allocate PV capacity among countries. The currently discussed pan-European feed-in tariff system for PV would be a step in this direction. Moreover, an internationally concerted effort to foster PV market growth could also incorporate developing countries where PV electricity could reduce power scarcity. Such efforts would need to include aspects such as coping with higher country-level risk ratings and the finance modalities for feed-in-tariffs which are already discussed in policy circles and the finance sector (Deutsche Bank, 2010). In summary, supranational demand-pull policy schemes will be difficult to achieve. However, even striving for such schemes potentially helps forge multilateral coalitions that could further develop clean technology markets.

7 Conclusion

This study contributes to the question of how the locus of policies influences the effect of technology-push and demand-pull policies on innovative output for the case of solar PV technology. Three key findings emerged. First, the study shows that domestic technology-push policies exclusively lead to innovative output within national borders. Second, domestic as well as foreign demand-pull policies trigger innovative output in a country. Third, we find no indication that market growth induced by domestic demand-pull policies triggers more innovative output than market growth induced by foreign demand-pull policies. While the domestic innovation benefits of technology-push policies seem to accrue exclusively to national innovators, demand-pull policies suffer from country-level innovation spillovers which are a disincentive for policymakers to engage in domestic market creation. Therefore policymakers should strive to coordinate demand-pull policy schemes on a supranational level in order to balance the effects of innovation spillovers.

This study is not without its limitations, and thus future research should contribute to further advancing our understanding of policy-induced technical change – particularly along the following four avenues. First, while patent counts are a widely accepted proxy for innovation from R&D projects, they only partially reflect progress through learning-by-doing (e.g., process innovations) and do not capture economies of scale. Future research should also consider learning-by-doing and scale effects as these are particularly sensitive to demand-side factors. Second, understanding the impact of policies on innovative activity within organizations, in particular on the trade-off between R&D and generating scale and learning by doing through production growth, should receive greater scrutiny, as such actor level mechanisms ultimately determine how policy signals translate into technical change. This probably requires detailed cross-case analyses of companies, for example in the solar PV sector. Third, while this study focused on the aggregate level of policy determinants, the effect of specific policy instruments, their particular design features, and their combination also needs to be analyzed. Fourth, a further limitation of this study is the focus on a single technological field. Further research should therefore concentrate on the question of how technology characteristics influence the link between policy determinants and technical change.

Appendix A

To test for endogeneity we chose the two step approach followed by Brynjolfsson and colleagues (2011). We first regress the potentially endogenous variable domestic public R&D funding on instrument variables and the remaining independent variables (from model A) using a log-linear model. We then include the residuals of this estimation as an independent variable in our original model and test the null hypothesis: domestic public R&D funding is exogenous. We reject the null hypothesis in case the coefficient of the variable 'residuals' is significantly different from zero.

As instrument variables we chose the annual public R&D funding for solar thermal technologies, biofuels and wind power. These are relevant instruments for two reasons. First, the patent activity in solar PV is independent of the instrument variable: Funding for other renewable energy technologies is very unlikely to impact research and development in solar PV. Second, public R&D funding in solar PV correlates well with the funding for other renewable energy technologies since governments typically do not overly differentiate between the various types of renewable technologies when changing the budget for public R&D. For example, after the first oil price shock governments, did not only increase R&D funding for solar PV but also for other renewable energy technologies (see also Dechezleprêtre and Glachant, 2011).

In Table A.1 we present the estimated coefficients of models A (claimed patents) and C (triadic patents) including the variable 'residuals'. In both models the coefficients of 'residuals' are not significantly different from zero. We hence fail to reject the null hypothesis that domestic public R&D funding is exogenous.

Table A.1: Estimated coefficients of the negative binomial fixed effects model for 15 OECD countries 1978 – 2005, including the variable ‘residuals’

	Model A	**Model C**
Dependent variable	**Claimed patents**	**Triadic patents**
Domestic R&D funding	0.301** (0.105)	0.299* (0.126)
Continental R&D funding (excl. domestic)	-0.001 (0.067)	0.025 (0.079)
Domestic capacity	0.137*** (0.028)	0.187*** (0.033)
Continental capacity (excl. domestic)	0.243*** (0.034)	0.245*** (0.036)
Crude oil price	0.006* (0.003)	0.007* (0.003)
Time trend	0.255* (0.102)	0.174 (0.106)
Residuals	0.039 (0.092)	0.077 (0.109)
Country fixed effects	Yes	Yes
Intercept	-1.354*** (0.350)	-2.103*** (0.407)
AIC:	1353	1090
Mean number of patents:	10.96	5.82
Fitted mean:	10.07	5.27

Notes: Heteroskedasticity and autocorrelation consistent errors in parentheses (full period, N=332); † $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Appendix B

Table B.1: Estimated coefficients of the negative binomial fixed effects model for 15 OECD countries 1978 – 2005, all patents

	Model E	**Model F**
Dependent variable	**All patents**	**All patents**
Domestic R&D funding	0.162** (0.060)	0.141* (0.058)
Continental R&D funding (excl. domestic)	-0.035 (0.072)	-0.067 (0.077)
Intercontinental R&D funding	--	-0.064 (0.240)
Domestic capacity	0.055† (0.032)	0.036 (0.034)
Continental capacity (excl. domestic)	0.153*** (0.035)	0.129*** (0.039)
Intercontinental capacity	--	0.067† (0.040)
Crude oil price	0.013*** (0.003)	0.013*** (0.004)
Time trend	0.341** (0.106)	0.273* (0.111)
Country fixed effects	Yes	Yes
Intercept	-1.114** (0.415)	-0.734 (1.283)
AIC:	1944	1945
Mean number of patents:	62.66	62.66
Fitted mean:	73.29	72.95

Notes: Heteroskedasticity and autocorrelation consistent errors in parentheses (full period, N=374); † $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Table B.2: Correlation matrix of independent variables, 1978 - 2005

	Independent variable	1	2	3	4	5	6	7	8
1	Domestic R&D funding	1.000							
2	Continental R&D funding (excl. domestic)	-0.336***	1.000						
3	Intercontinental R&D funding	-0.086	-0.302***	1.000					
4	Domestic capacity	0.527***	-0.296***	0.147**	1.000				
5	Continental capacity (excl. domestic)	-0.066	0.422***	0.030	0.201***	1.000			
6	Intercontinental capacity	0.106	0.070	0.095	0.559***	0.743***	1.000		
7	Crude oil price	-0.260	-0.002	0.505***	-0.231***	-0.331	-0.488***	1.000	
8	Time trend	0.090	0.049	-0.090	0.493***	0.687***	0.842***	-0.728***	1.000

* p < 0.05; ** p < 0.01; *** p < 0.001

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PAPER III

The Effect of Demand-Pull Policies on Innovation in Different Technology Life-Cycle Stages – the Case of Wind Power

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Abstract

This paper re-examines the effect of demand-pull policies on innovation in the case of wind power, applying an evolutionary perspective on the technology life-cycle and the role of diversity in the development of a technology. Using econometric analysis of a panel of patent data, we find that demand-pull policies triggered more innovation in the era of a dominant paradigm than in the era of competing paradigms. We conclude that the level of diversity should be considered when applying demand-pull policies.

JEL codes: B52, O38, Q42, Q55

Keywords: demand-pull policy, diversity, patent counts, technological paradigms, technology life-cycle

1 Introduction

Maintaining economic growth amid societal concerns such as climate change and resource depletion inevitably calls for substantial technical change (UNEP, 2011). However, most clean technologies are still in an emerging stage and are rarely competitive (IEA, 2011). Furthermore, the marginal social and private surpluses of such technologies are often far from congruent due to the negative externalities of conventional alternatives. To support the diffusion of clean technologies, governments have made extensive use of demand-pull policies that address either negative market externalities or directly subsidize clean technologies (IEA, 2004, 2007).[1] Besides their effect on diffusion, important justifications for demand-pull policies in environmental politics are their benefits in the form of (i) incentives for firms to innovate, and (ii) experience gained in production, field tests, and prolonged use, all of which enhance the competitiveness of clean technologies. Indeed, many studies in the field of environmental economics have come to the conclusion that demand-pull policies ‘induce’ innovation (e.g., Del Rio Gonzalez, 2009).[2]

Yet, unresolved issues remain regarding the workings within the ‘black-box’ of policy-induced innovation (see Kemp and Pontoglio, 2008, for a discussion on policy-induced environmental innovation). Contingency factors on the supply side of emerging industries, such as technology or time-specific phenomena in the development of new technologies, have thus far received relatively little scrutiny in environmental economics. In quasi-evolutionary conceptions of technical change, however, market signals are assumed to be a necessary rather than a sufficient condition for innovation (Dosi and Soete, 1988), and demand and technology are regarded as developing in a co-evolutionary process (Kleinknecht and Verspagen, 1990; Malerba, 2006). Under certain conditions, the evolution on the supply side will take the form of a life-cycle, which describes patterns of diversity over time: Typically, the emergence of a new technology initiates an era of high technological uncertainty and diversity, which is followed by a selection process culminating in a phase of relatively high standardization and low diversity (Abernathy and Utterback, 1978; Anderson and Tushman, 1990; Klepper, 1997). Rather than representing pure economic inefficiency, it is argued that diversity has a positive impact on innovation (Stirling, 1998, 2007): The ‘breadth’ of (technological) starting points as well ‘complementarities’ that increase with the number of options are assumed to be conducive for innovation (Cohen and Malerba, 2001).

However, until now this argument about the effect of diversity on innovation has not been taken up by empirical scholars when analyzing demand-pull policies. In fact, the innovation effect

[1] We use the term ‘demand-pull’ policies for all measures that incentivize the adoption of technologies, i.e., measures that directly address externalities, such as pollution taxes or tradable emission permits, as well as for command-and-control regulation, feed-in tariffs, and technology portfolio standards.

[2] Reviews of these studies can be found in Jaffe et al. (2002), and Carraro et al. (2010).

of demand-pull policies is assumed to be positive and either *constant over time*[3] (e.g., Johnstone et al., 2009) or *steadily diminishing over time*[4] (e.g., Junginger et al., 2010). Yet, since diversity tends to change as a technology evolves, this assumption possibly neglects diversity as a relevant determinant of innovation. As a consequence, and depending on the innovation impact of diversity, demand-pull policies might have to be tailored to specific life-cycle phases of a technology.

We address this gap by investigating the question of how demand-pull policies impact innovation in different phases of the technology life-cycle. To do so we present an econometric patent panel data analysis of the evolution of wind power technology in 15 OECD countries between 1978 and 2002.

In the following, the paper first outlines an evolutionary perspective on the effect of demand-pull policies on innovation (section 2). After describing the research case in section 3, it provides details on the data and methodology of the analysis (section 4). In section 5 the paper presents results, which are then discussed in section 6.

2 An evolutionary perspective on the effect of demand-pull policies on innovation

In this section we develop an evolutionary perspective on the effect of demand-pull policies on innovation, one that depends on the level of diversity in an industry. We use the concept of technology life-cycle stages to define two distinct levels of diversity. First, to better understand the direct impact of diversity on innovation, the relationship between these two constructs is investigated (2.1). We then briefly review the literature on technological paradigms (2.2) in order to model the technology life-cycle as patterns of paradigmatic diversity and convergence (2.3) This allows us to derive a hypothesis regarding the moderating effect of the technology life-cycle on the relationship between demand-pull policies and innovation (2.4).

2.1 Diversity and its impact on innovation

From an evolutionary perspective, technological and organizational diversity is rooted in the heterogeneity of firms. Firms are understood as 'boundedly rational' agents that operate with an 'imperfect understanding' of their environment due to significant cognitive limitations (Nelson and Winter, 1982). To cope with the ever-present complexity and selective pressures, they make use of 'routines' (Cohen et al., 1996), which may refer to input-output transformation processes of production but also, on a higher level of hierarchy, to heuristics that guide change and search

[3] This is typically assumed in studies analyzing the effect of policies on innovation using patent counts.
[4] When analyzing the effect on costs, e.g., in the case of so-called 'learning curves'.

processes such as the annual allocation of funds to R&D (Winter, 1964). Conditional on their routines, firms interpret technological opportunities and market incentives before and while engaging in different types of learning (which may result, in turn, in the introduction of innovations). Technological and organizational innovation go hand in hand, as the corresponding technological knowledge is largely localized, intertwined with organizational routines, and partly tacit in nature (Winter, 1984). The tacitness of technological knowledge and the self-reinforcing nature of many learning mechanisms give rise to persistent path-dependency, micro-level heterogeneity and, thus, organizational and technological diversity (Dosi, 2007).

This system-inherent diversity is considered conducive to innovation (Gibbons and Metcalfe, 1986; Saviotti and Ziman, 1998). Cohen and Malerba (2001) describe two effects that lead to innovation in times of high diversity. First, in any given technological path innovation opportunities tend to be exhaustive. This is for example reflected in diminishing returns to R&D, or the "sharply diminishing returns" found for learning-by-doing (Arrow, 1962: 155). In the face of a wider range of alternatives, the learning of actors may therefore result in more innovation ('breadth effect'). Second, benefits of diversity may be rooted in synergies which can occur when insights from alternative approaches are combined ('complementarity effect').

2.2 Technological paradigms as patterns of innovation

Despite the existence of system-inherent heterogeneity, collective, aggregate patterns of innovation do exist. Routines are understood as being "shaped by the learning history of the agents, their pre-existing knowledge and, most likely, also their value systems and their prejudices" (Dosi and Nelson, 1994: 159). In many sectors, 'creation' and 'selection' proceed with "a certain inner logic of [their] own" (Nelson and Winter, 1977: 56), as communities of agents that interact and perceive similar environments align their actions according to a 'technological paradigm' (Dosi, 1982; Dosi, 1984).[5]

The explanatory power of technological paradigms is rooted in their ability to combine two largely distinct streams of literature. On the one hand, there is much overlap with the literature investigating the pervasiveness of specific technological artifacts that remain almost invariant over time, also referred to as 'technological guideposts' (Sahal, 1981, 1985), 'dominant designs' (Abernathy and Utterback, 1978; Klepper, 1997), or 'lock-ins' (Arthur, 1989; David, 1985). Accordingly, the stickiness of technological paradigms may be explained by purely technological factors (e.g., by increasing returns to adoption). On the other hand, the conceptualization of

[5] Technological paradigms, in analogy to Kuhn's (1958) scientific paradigms, can be found in the form of stylized common denominators of technology and heuristics at different levels of abstraction. While Freeman and Perez (1988) identify 'techno-economic' paradigms on the macro-economic level ('the information technology paradigm'), Dosi's (1982) level of analysis is that of 'technological paradigms' on the industry

technological paradigms reflects that actors often intuitively share heuristics to deal with future directions of a technology (Dosi, 1988). Therefore, a technological paradigm is reconcilable with cognitive concepts of 'meta-standards' (Metcalfe and Miles, 1994), and 'cognitive frames' (Kaplan and Tripsas, 2008; Orlikowski and Gash, 1994).

As such, a technological paradigm "create[s], in any given historical era, a set of opportunities and constraints for innovative activities" (Castellacci, 2007: 1110), specifying a technological 'trajectory' or 'innovation alley'. It leaves firms with selected innovation alternatives, structures the innovation process, thereby reduces uncertainty and "implicitly speeds up problem solving" (Nightingale, 2008: 533). Most technical change will proceed along a 'common' path as agents try to solve 'critical problems' (Rosenberg, 1976).

The concept of paradigms is well suited to model diversity over the technology life-cycle, since the diversity within a technological field present is in fact inseparably linked to the number of coexisting but different paradigms. This becomes particularly apparent when using attributes of diversity introduced by Stirling (1998, 2007). He defines 'variety' (number of options), 'disparity' (degree of differences between options), and 'balance' (evenness of options) as constituting properties of diversity. While disparity within paradigms will be relatively low, across paradigms it may be considerable. The balance in a system may be modeled as the relative prevalence of different paradigms; the emergence of an additional paradigm would hence increase diversity as variety, disparity and balance increase.

2.3 Technology life-cycles as patterns of diversity

The term 'life-cycle' is a popular metaphor to describe patterns of technological development and convergence. Significant differences within the extensive body of literature lie in the space in which convergence is assumed and/or observed (artifact or cognitive level), the level of granularity (system, product or component) and the proposed selection mechanisms leading to convergence. However, a commonality of all studies is a convergence to a dominant design or paradigm, effectively describing a pattern of changing diversity within an industry over time.

For example, Utterback's and Abernathy's life-cycle model (1978; 1975) focused on industrial innovation and emphasized the role of the supply-side. In their model, a technological discontinuity is followed by a period of high product diversity and uncertainty. As uncertainty decreases, a dominant design emerges and the focus of innovation shifts from product design towards process technology. Building on this concept Anderson and Tushman (1990) present a life-cycle model in which product innovation continues in the era of a dominant design, yet only on an 'incremental' level. Similarly, Murmann and Frenken (2006) argue that the stability implied in the

level (such as the 'solar paradigm'). In this study, we go one level further down and investigate different paradigmatic approaches within wind turbine technology.

notion of dominant designs is confined – in most cases – to core components; at the same time, innovation may surge in peripheral parts and on lower hierarchical levels of system technologies (Metcalfe and Miles, 1994). The literature on industrial dynamics links the notion of technology life-cycles to patterns of firm entry and exits (Klepper, 1996, 1997), hinting at a strong and persistent linkage of technology and firm-level routines and capabilities. Dosi and Nelson (2010) stress that a necessary condition for a dominant design is convergence on a cognitive level, in the form of a 'dominant paradigm'.[6]

While some life-cycle models explicitly state that diversity decreases as a convergence takes place (e.g., Utterback and Abernathy (1978; 1975)), this holds true for all these models when applying Stirling's conception of diversity (see section 2.2). The disappearance of a paradigm will reduce diversity along with reductions in variety, disparity and balance. Even if non-dominant designs or paradigms do not vanish entirely during convergence, diversity will decrease due to a reduction in 'balance'.

In summary, technology-life cycle stages are a good proxy for phases of high and low diversity since the life-cycle as such is a stereotypical pattern of diversity over time. In the subsequent section we therefore build on the concept of technology life-cycles and explore the effect of demand-pull policy on innovation in the era of competing paradigms (high diversity) and in the era of a dominant paradigm (low diversity).

2.4 The effect of demand-pull policies on innovation

When investigating the effect of demand-pull policies on innovation, scholars typically assume the innovation effect of demand-pull policies to be positive and constant over time. However, if we model technology life-cycles as patterns of diversity and understand diversity as conducive to innovation, a differentiated picture arises regarding the impact of demand-pull policies on innovation. Below we first subsume the positive innovation effects of demand-pull policies presented in the literature on 'induced innovation' and 'niche markets' under the term *policy-induced learning*. Second, the moderator *'technology life-cycle stage'* is discussed, which questions the implicit assumption that innovation effects are constant over time. Lastly, we hypothesize on how the effect of demand-pull policies on innovation deviates between different life-cycle stages (see Figure 1).

[6] Conversely, a dominant paradigm is not sufficient for convergence on the artifact level. This includes mature sectors where a dominant design never emerged. According to Malerba, (2002, p. 259), dominant designs will emerge only in sectors "characterized by a system product and consumers with a rather homogeneous demand".

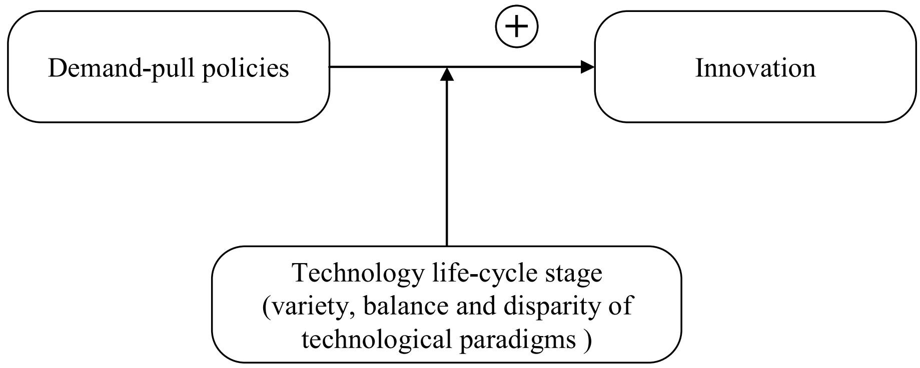

Figure 1: Model depicting the impact of demand-pull policies on innovation

Policy-induced learning: An increase in demand-pull policy support will increase commercial activity and the resources available in an industry. This triggers at least three learning mechanisms that contribute to innovation. First, prospects of a growing market likely lead to increasing corporate R&D investments, which facilitate systematic, formalized 'learning-by-searching' (Schmookler, 1962). In addition, companies with products at the commercial stage benefit from increased sales and slack resources, which often routinely result in higher R&D budgets (Cohen et al., 2010; Granstrand, 1998). Second, a growing market will result in increased production, which enables 'learning-by-doing' (Arrow 1962). Third, the inseparability of innovation and diffusion implies that 'learning-by-interacting' - particularly between users and producers - is endogenous to increased deployment (Lundvall, 1985; Lundvall, 1988).[7] In sum, policy-induced learning as triggered by demand-pull policies positively impacts innovation.

Moderator 'technology life-cycle stage': As outlined in section 2.1, it is assumed that diversity has a positive impact on innovation due to the 'breadth' and the 'complementarity' effect. While we outlined above that demand-pull policies foster innovation through learning mechanisms, the question arises whether the level of diversity moderates the effect of demand-pull policies on innovation. During an era of competing paradigms (high diversity), demand-pull policies lead to learning within a broad set of technological options, whereas during an era of a dominant paradigm, learning occurs in fewer technological options (low diversity). Therefore, conditional on diminishing returns to R&D and informal learning processes, a given amount of demand-pull policy funding is likely to trigger more innovation in an era of competing paradigms. Moreover, policy-induced learning is further increased through synergies with other technological options. These synergies are also more prevalent at times of high diversity.

To conclude, the technology life-cycle stage – which we use as a proxy for two distinct levels of diversity – moderates the impact of demand-pull policies on innovation (see Figure 1). While this impact is known to be positive across different phases of a technology life-cycle, we

[7] Note that we include here what others have termed 'learning by using' (e.g., Rosenberg, 1982).

expect it to be more positive in an era of competing paradigms than in an era of a dominant paradigm. We therefore hypothesize:

> **Hypothesis:** *Demand-pull policies will trigger more innovation in an era of competing paradigms than in an era of a dominant paradigm.*

3 Research case – wind power

The wind power case appears well-suited for testing the above hypothesis for three reasons: First, its technological development was intimately tied to government actions throughout the history of wind power (Ackermann and Söder, 2002; Strachan et al., 2010). Worldwide installed capacity for wind power has been growing rapidly (see Figure 2) driven by a variety of governmental support schemes, which allocated public funds on the order of billions of USD.[8] Second, after the emergence of different paradigms by the mid-1970s, the technology went through two distinct periods of development, one with several competing paradigms until about 1990 and one with a widespread, dominant paradigm thereafter. Third, patenting activity, an important indicator of innovation, has been dynamic over several decades (see Figure 2) and even though the technology is still not competitive with fossil energy, costs and reliability of wind power utilization have been greatly improved in recent decades (e.g., Schilling and Esmundo, 2009). Below we briefly outline the outstanding role of policy support for the development of wind power technology. We then describe the technological paradigms that emerged in the 1970s and show how they evolved over time.

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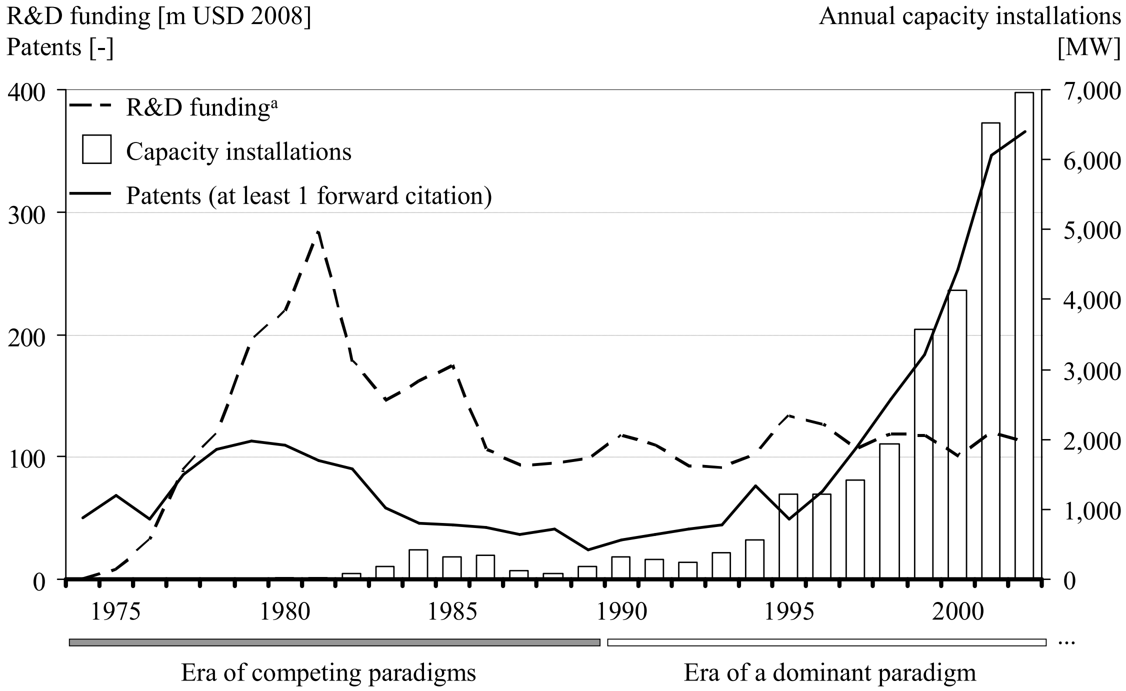
[8] All monetary values are provided in 2008 USD.



a Top 15 countries in terms of pateneting activity

Figure 2: Development of wind turbine technology and policy support

3.1 Policy support

Although governments had long contemplated using domestic wind power as a potentially cheap source of electricity, it was not until the early 1970s that the oil crises and growing anxiety about nuclear energy initiated efforts to utilize wind power to provide a significant portion of electricity generation. While initially governments primarily provided public R&D funding to develop wind power technology, as of the early 1980s the focus started to shift towards demand-pull instruments. Today demand-pull policy funding exceeds public R&D funding by an order of magnitude. Below we provide a brief overview of both policy categories.

On the one hand public R&D funding for wind power technology has been provided since the mid 1970s, particularly by governments in the US and Germany. In the early years aerospace companies received most of the funding as their capabilities were believed to be best suited for wind power innovations. By 1981 funding had grown to 284 million USD per year. However, the mid 1980s saw the end of the most ambitious research projects. Political disillusionment concerning the future of wind power as an economic, domestic energy source spread and, amid declining oil prices, governmental R&D spending fell to around 100 million USD per year and remained rather constant thereafter (Figure 2).

On the other hand, during the period from 1978 to 1989, a variety of demand-pull policies in the U.S. (mainly in California), Denmark, Germany and The Netherlands led to the formation of early markets for wind turbines. The U.S. and Denmark accounted for more than 95% of global wind turbine capacity installations through 1989 and hosted most of the commercially successful wind turbine manufacturers. In Denmark, an investment subsidy for wind power project developers and the obligation for utilities to purchase the produced electricity fostered the steady growth of the market for small turbines and the corresponding industry starting from the late 1970s. Together with the pledge of Danish utilities to invest in wind power in 1985, this led to 326 megawatt (MW) of installed capacity from 1979 through to 1990 (~15% of the global market during that period). In the U.S., governments introduced federal and state subsidies for wind power investors based on the 'Energy Tax Act' in 1978. This financial support was complemented by the Public Utility Regulatory Policies Act (1978) that required the utilities to buy power from independent producers at avoided cost rates. This institutional set-up led to the 'California Wind Rush' (Reason and Coates, 1994), resulting in a total of roughly 1,800 MW installed wind turbine capacity by 1990 (then some 80% of the global market): almost double the state goal issued in 1980 (Karnøe, 1990). Fluctuations in annual installations were remarkable, with growth rates of more than 300% from 1981 to 1984, followed by a sudden collapse when the Reagan administration decided not to extend tax credits beyond 1985. Overall, the outcome of governmental interventions in the 1980s was rather sobering: Cost targets were clearly missed and the industry underwent a severe crisis as of the mid- 1980s. From the early 1990s on the focus of governmental support converged on the promotion of commercially viable turbines. Governments adopted combinations of demand-pull policy instruments, particularly feed-in tariffs, investment subsidies and/or tax breaks.[9] In the 1990s, Germany, Spain, Denmark and the U.S. accounted for about 75% of globally installed capacity. By 2010, the cumulative installed capacity had surged to a total of 170 GW, with China and the U.S. accounting for the lion's share in a more fragmented market (IEA, 2010d).

3.2 Evolution of technological paradigms in wind power since the 1970s

The approaches to technological development that emerged after the first oil crisis until the mid 1970s were intriguingly different. It was a "commonly held view … that wind technology was not that complicated and that only large scale wind turbines would be able to contribute significantly to the supply of energy within a short period of time" (Karnøe, 1990:110). Therefore governmental support was mainly directed towards efforts attempting to centuple the then-current size of wind turbines (used for battery charging or connected to remote, local grids). Governments initiated R&D programs for MW-scale wind turbines and awarded demonstration projects to domestic aerospace companies, whose know-how was considered best suited for the technology (Gipe, 1995; Hau et al., 1993). However, in parallel, entrepreneurs and SMEs, much more skeptical about the technological feasibility of large-scale plants, started to develop small-scale designs to supply

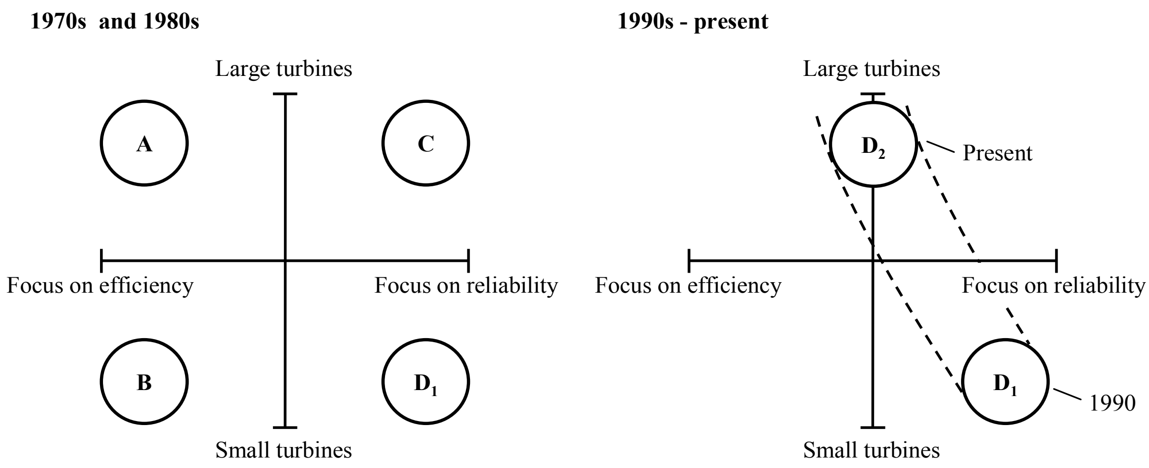
[9] An overview of the myriad of policy instruments is given in Sawin (2001) for the U.S., Germany, and Denmark; in Kamp (2010) for the Netherlands; in Strachan et al. (2010) for Spain, the U.K. and Ireland; in Söderholm et al. (2007) for Sweden; and in IEA (2004) for other countries. Furthermore, the IEA (2007) maintains a thorough database.

turbines for idealistic early adopters and in anticipation of future market subsidies (Kamp et al., 2004; Stoddard, 1990).

Besides the turbine size, design approaches differed in terms of the knowledge base and degree of scientific sophistication; i.e., what scholars called the firms' 'technological styles' (Heymann, 1998), 'paths' (Garud and Karnøe, 2003), or 'design philosophies' (Stoddard, 1986). Garud and Karnoe (2003) polarized these differences for turbine suppliers in Denmark and the U.S.: On the one hand, Danish firms focused on reliability and pursued a path of incremental improvement building on craft tradition and design methods from machinery engineering ('bricolage'); on the other hand, U.S. manufacturers concentrated on high turbine efficiency and attempted 'breakthroughs' in designs based on light materials. While Garud and Karnoe (2003) focused on small turbine manufactures in the two countries, the frames of 'bricolage' and 'breakthrough' are useful concepts to group the polarized approaches found around the world, for both small and large turbines.

What results is a matrix of four main paradigms that emerged in the 1970s (see left matrix in Figure 3). Paradigm A represents what Gipe (1995) described as 'Giant Killers': megawatt scale turbines designed using aerospace know-how and methods; this paradigm was particularly dominant in the governmental demonstration projects in the US, Canada and Europe (except Denmark). Moreover, there were start-ups, spin-offs and SMEs in the U.S. and Europe that adhered to a 'light-weight' paradigm (B). They used aerospace codes to design small, light turbines and followed this rationale to master the complexity of large-scale turbines through continuous scaling. Paradigm C ('large Danish') comprises large turbines built for demonstration projects in Denmark (which had no aerospace industry to develop). The designs were modified versions of the so-called 'Gedser' design (Hau, 2006) including turbines, which were heavy, relatively simple, and cheaper than their counterparts originating in the aerospace industry. Firms applying paradigm D_1 ('small Danish') in contrast to the other three did not rely on formal development processes but on trial-and-error, learning-by-doing and hands-on engineering expertise. The paradigm emerged from a 'grassroots' movement in Denmark with idealists building small, heavy and reliable turbines based on the Gedser design. Later entrepreneurs and manufacturers of agricultural machinery took up their technology and established a rapidly growing industry (Karnøe, 1993).

The diversity that emerged in the 1970s was considerable, leading Bergek and Jacobsson (2003) to use the term "phase of experimentation" for the period up to 1990. Ultimately, the 'small Danish' turbines outperformed all other much more sophisticated designs and emerged as the dominant paradigm (D_1). Subsequently, the paradigm evolved further as companies embraced formal R&D processes and began to focus on both efficiency and reliability (D_2) (see Figure 3, top right).

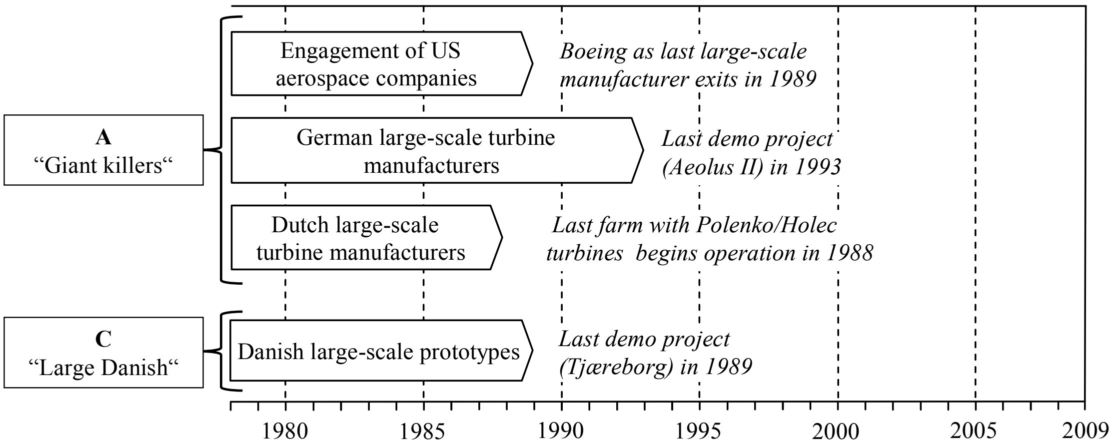


	1970s and 80s				1990s – present
Paradigms	**A: "Giant killers"**	**B: "Light-weight"**	**C: "Large Danish"**	**D_1: "Small Danish"**	**D_2: "Danish design"**
Turbine size	Up to 4 MW	Up to 300 kW	Up to 2 MW	up to 200 kW	Continuous up-scaling, currently >5 MW
Design objective	Efficiency (kW/kg)		Reliability (minimize breakdowns)		Efficiency & reliability (LCOE[a])
Design character-istics	Light materials, high rotor speed, often 2-3 blades, upwind, horizontal or vertical axis	Light materials, high rotor speed, various designs	Gedser/modified Gedser design: heavy materials, low rotor speed, 3 blade upwind, horizontal axis		Modified Gedser design:, light materials, low rotor speed, 3 blade upwind, horizontal axis
Type of innovation	Radical / 'breakthrough'	Radical / 'breakthrough'	Rather incremental	Very incremental	Rather incremental
Knowledge base	Aerospace	Aerospace	Machinery engineering (science)	Machinery engineering (craftsmanship)	Wind turbine-specific knowledge (aerodynamics, structural mechanics)
Key actors	Aerospace companies (e.g., Boeing, General Electric, MAN) Universities (e.g., Stuttgart U.), government departments (e.g., US Department of Energy, GER Ministry for Research and Technology)	SMEs, spin-offs, start-ups, some larger companies (e.g., MAN, US Windpower) Universities (e.g., U. of Massachusetts), government departments (e.g., US Department of Energy)	Danish utilities (ELSAM), SMEs (e.g., Vølund, Danish Wind Technology) Danish Academy of Technical Science	"Grassroots movement", later SMEs and start-ups (e.g., Vestas, Bonus), Japanese MNCs (e.g., Mitsubishi) Danish Windmill Manufacturers Association, Danish Windmill Owners' Association, Risø Test Centre (DK)	Large pure-play companies (e.g., Vestas, Enercon); MNCs (e.g, General Electric, Siemens, Mitsubishi)
Main policy support	R&D funding, demonstration projects	R&D funding, market subsidies	R&D funding, demonstration projects	Test facility (Risø), market subsidies	Market subsidies

a LCOE: levelized cost of electricity.

Figure 3: Evolution of wind power paradigms and its characteristics; Source: Gipe (1995); Bailey and Viterna (2011); Righter (1996); Heymann (1995, 1998), Bergek and Jacobsson (2003) Hendry and Harborne (2011); Garud and Karnøe (2003); Kamp et al. (2004); Karnøe (1990, 1993, 1995), Sawin (2001)

a) Firms with turbines at pre- or early commercial stage (periods of activity)



b) Firms with turbines at commercial stage (percentage of firms in the market)

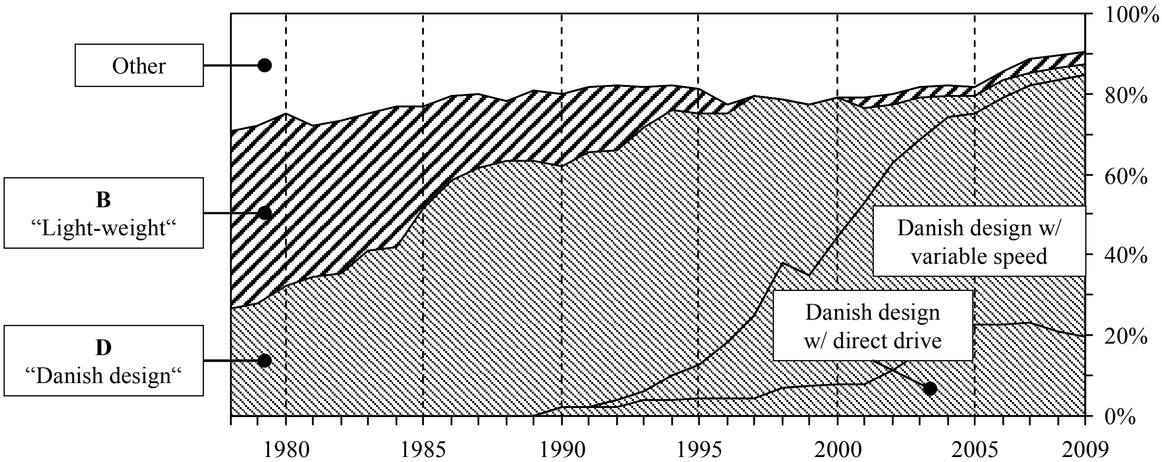


Figure 4: Development of wind power paradigms over time; Source: Heymann (1995), Gipe (1995), Johnson and Jacobsson (2000), Menzel and Kammer (2011)

It is difficult to assign a specific date to the resolution of the competition between paradigms. In the case of the mostly pre-commercial large-scale turbine paradigms, 1989 appears to mark the transition. This was when Boeing, the last of the firms involved in the massively funded U.S. federal wind R&D program (paradigm A) exited the industry and when the last ‘large Danish’ prototype was erected (paradigm C) (see Figure 4).[10] The share of firms with products at the commercial stage (from the two small-scale turbine paradigms) pursuing the Danish approach rose sharply in the mid-1980s, when the end of policies in California resulted in a massive shake-

[10] While in 1993 Messerschmitt-Bölkow-Blohm (MBB) - a large German aerospace company at that time - installed another privately funded megawatt-scale prototype, we consider this an outlier in face of an annual market volume of several hundred MW that had developed in the commercial market in the meantime.

out of firms producing light-weight turbines. From 1987 on, more than 60% of manufacturers used the ‘Danish design’ (see Figure 4) and Danish firms held around 80% of the global market share (Garud and Karnøe, 2003). As of 1990 the ‘light-weight’ paradigm B – already in a niche position – nearly disappeared until the mid 1990s. Based on the evolution of paradigms A – D, we assume the ‘Small Danish’ paradigm to have emerged as the dominant one in 1990. (This is consistent with Bergek and Jacobsson (2003), but we will nonetheless test for sensitivity regarding the exact phase split.) In the remainder of the paper, we will thus analyze the impact of demand-pull policies in the ‘era of competing paradigms’ (high diversity) prevailing from 1978 – 1989 as well as in the ‘era of a dominant paradigm’ (low diversity) as of 1990.

4 Data and Methodology

To investigate the hypothesis outlined above, we econometrically analyzed a set of patent data on a panel of 15 OECD countries in the period 1978 through to 2002. Details on the panel analysis are provided below. After explaining the measurement of the dependent variable "innovation" based on patent counts, we illustrate the operationalization of determinants and controls. Lastly, we specify the regression model.

4.1 Innovation

This work uses patent counts as a proxy for innovation. Patents’ intrinsic variability poses two major challenges to their use in economic analysis (Griliches, 1990). First, an unambiguous assignment of a large number of patents to any kind of classification is difficult. A meaningful data set can be obtained, however, if an adequate search methodology is applied. Second, variability also implies that patents “differ greatly in their technical and economic significance” (Griliches, 1990: 1666), which calls for the use of a patent value criterion in order to transform patent counts from a measure of pure *invention* to a proxy for *innovation* (Hall et al., 2001).

For the search strategy, a combination of keywords and International Patent Classifications (IPC) was chosen so as to reduce potential errors to a minimum. The search string only targets patents related to electricity generation based on wind power.[11] It was developed through a two-step procedure (using the Derwent World Patent Index, WPI). First, we compiled a list of keywords extracted from the literature (e.g., Margolis and Kammen, 1999; Nemet, 2007) and from patents assigned to the obvious IPC ‘wind motors’ (F03D). Four industry experts provided feedback on the identified keywords. Then we iteratively curtailed the keyword list by applying it to F03D and manually checking random samples for irrelevant patents. Second, additional IPC listed in the 'Green Inventory' of the World Intellectual Property Organization (WIPO, 2010) were added to the search string, as were classes identified by analyzing additional IPC that relevant F03D patents were assigned to. Final tests to validate the search strings' quality indicate about 5% false positives and 10-15% false negatives.[12]

In order to address the skewed nature of patent value, we used the number of citations received from subsequent filings (forward citations) as a value criterion. Forward citations correlate well with a patent's value (Albert et al., 1991; Carpenter et al., 1981; Pavitt, 1988; Trajtenberg, 1990). Studies have demonstrated, inter alia, the correlation of citations with (i) the market value of the patent (Harhoff et al., 1999), (ii) the market value of the company (Hall et al., 2005) and (iii) the company's financial performance (Narin et al., 1987).

For the standard specification of the dependent variable, we counted patents filed in a country in a given year that received one forward citation ('citation threshold') within five years after application ('citation window').[13] A 'citation window' is necessary to give each patent equal chance to receive citations and make patent counts intertemporally comparable. The choice of a five-year time window is consistent with previous studies (Hall and Ziedonis, 2001; Narin and Olivastro, 1993; Nemet, 2009; van Zeebroeck, 2011).[14] Due to the use of patent families and other lags in the patent data (see Appendix A), this methodology requires a buffer of 8 years from the last year in the observation period to the date of search. Therefore our data are restricted to the observation period 1978-2002.

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[11] Most policies in the field of wind power after the 1973 oil crisis were designed to introduce wind power technology to markets for electricity (grid-connected or stand-alone). Hence, patents that do not explicitly and solely claim other purposes, such as wind-driven pumps, were included.

[12] Upper bound of false negatives: Share of the patents filed by the ten largest turbine manufacturers (ranked by sales in 2010), which were not found by our search string. Lower bound of false negatives: A random sample of 200 excluded patents assigned to the main IPC class FO3D (wind motors) was tested manually for relevance. In addition, we benchmarked our search string with alternative wind power search strings available in the literature. Our search string identified the highest share of patents filed by the ten largest turbine manufacturers (indicating the lowest share of false negatives), although our overall patent sample was comparatively small (indicating very few false positives).

[13] The distribution of patent values could potentially change over time. For example, patents during the era of competing paradigms might have been on average more valuable and 'radical' than during the era of a dominant paradigm. To further control for changes in patent value distribution, we constructed additional variables with five forward citations (as in Nemet, 2009) and with patent counts that were filed in at least two countries (as in Harhoff et al., 2003). Results are reported in the appendix. For data availability reasons we did not use value criterions such as patent scope, i.e., the number of IPC per patent (Lerner, 1994) or the outcome of opposition cases (Harhoff et al., 2003).

[14] The length of a 'citation window' is a trade-off between the length of the observable period and methodological validity. The considerable uncertainty concerning the technological and economic value of a patent, which is typically filed in the early stages of a research project, makes it necessary to allow at least for a minimum period after which most of the uncertainty about the patent value is resolved (Pakes' (1986) data imply a minimum period of around 3-4 years). A window of more than five years is of little use, since only a few patents receive their first citation after a longer period (Narin and Olivastro, 1993). A much shorter time window would allow too little time for the value uncertainty to be resolved (Pakes and Schankerman, 1984).

Patent family and citation data were extracted for 15 countries from the International Patent Family Database (INPAFAMDB) of The Scientific & Technical Information Network (STN, 2011).[15] The countries in the panel were selected based on patent activity and determinant data availability; the sampled countries account for roughly 70% of installed wind power capacity (as of 2009) and 70% of wind power patents in the observation period. To best capture the date and the location of an invention, the panel data use the patent application date (instead of the publication date) and the resident country of the inventor.[16]

4.2 Independent variables

4.2.1 Demand-pull policies

Scholars have long been "struggling with the problem of measuring environmental policy" (Kemp and Pontoglio, 2008: 6). Given the variety of instruments included in the definition of demand-pull policies affecting renewable energy, it is very difficult to provide reasonable estimations of actual policy expenditure. We use capacity additions in MW as a proxy for demand-pull policy. Thereby, we explicitly abstract from the policy instrument choice and only measure the impact of policy on the sales of turbines.[17] To render this a valid methodology, conditions imposed by three assumptions need to be fulfilled. (i) It is assumed that the distance to competitiveness is large enough that no capacity is installed without political support schemes. This is a reasonable assumption for wind power during the observation period (see section 3). The capacity of demonstration plants (which are also included in the R&D funding) constitutes some double-counting, but the corresponding capacity is small compared to the total capacity installed in the period of observation (Harborne and Hendry, 2009). (ii) The total costs per unit of added capacity are assumed to be constant over time. While capacity costs decreased over time, we address this simplification through robustness tests based on monetarized demand-pull variables in the results chapter. (iii) The innovation in a year is assumed to have no immediate impact on sales (i.e., no reverse causality). Since patents are typically taken out early in an R&D project (Griliches, 1990), this too can be considered a reasonable assumption.

The use of annual capacity additions (marginal demand) in the regression analysis implicitly assumes that the innovation effect occurs bundled in the year of installation. While this is, to a certain extent, adequate to measure learning-by-doing and learning-by -searching in the

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[15] Since this database contains the original documents in multiple languages (which leads to problems with the keyword methodology), the results were generated using the Derwent WPI and subsequently transferred to INPAFAMDB.

[16] Japanese patents and patents filed prior to 1990 are assigned to the country in which they are filed first ('priority country') for reasons of data availability.

[17] This approach to measuring the strength of the 'demand-pull' effect is similar to that of Schmookler (1962).

production of wind turbines, an operationalization that captures learning-by-interacting will have to be cumulative in some form. Therefore, cumulative capacity additions were used as a second demand-pull policy variable. Since besides domestic demand foreign demand – possibly to a lower extent – could also influence innovation (Dechezleprêtre and Glachant, 2011) both annual and cumulative installations are divided into domestic (DOM_CAPACITY and DOM_CAPACITY_CUM) and foreign capacity (FOR_CAPACITY and FOR_CAPACITY_CUM). Annual domestic capacity additions were compiled from various sources (Bergek and Jacobsson, 2003; Brown, 2011; CWPC, 2010; ENS, 2003; Gipe, 1991; IEA, 2010d, e).[18] To test the capacity variables' robustness, we also ran alternative model specifications with monetarized demand-pull variables (DOM_SUBS_PAID, FOR_SUBS_PAID). These were calculated using the difference between the levelized cost of electricity (LCOE) for wind power and the LCOE of the U.S. fossil fuel mix (Schilling and Esmundo, 2009), multiplied by the amount of electricity produced from wind power (IEA, 2010c).[19]

4.2.2 Control variables

Besides the modeled determinants of innovation, a set of other exogenous factors has to be accounted for, which we derived from the literature. We included two additional types of policy support which are potential determinants of innovation: First, direct governmental R&D funding (variable R&D; all prices are converted to 2008 USD prices at power purchasing parity, PPP) for wind power (IEA, 2010f).[20] Second, a dummy variable is used to account for the long-term policy orientation signaled by the Kyoto Protocol (KYOTO) – set at 0 until 1997 for all 15 countries and 1 thereafter.[21]

In addition to policy support, relative factor prices may impact innovation. Therefore, we controlled for world oil prices using an annual index (EIA, 2010, 2008 USD at PPP) (OIL_PR) and used national industry electricity prices (IEA, 2010b, 2008 USD at PPP) (ELECTR_PR) to account for substitutes. We also included the iron ore price in order to consider one of the most important

[18] Negative values were set to zero.
[19] All prices were converted to 2008 USD/kWh with the CPI (IEA, 2010a). Despite the 'back-of-the-envelope' character of this estimation, the values are fairly similar to estimations made by Gipe (1995) for the amount paid by Denmark and the U.S. for market subsidies through 1990. Gipe estimates the U.S. to have paid USD 900 m and Denmark USD 150 m from 1974 to 1992. If one assumes the prices to be unadjusted (arrived at by comparing the R&D spending described by Gipe with this study's data), this is equivalent to USD 1,800 m and USD 300 m in 2008 USD, compared to our estimation of USD 3,300 m and USD 550 m, respectively. The resulting difference of ~2 is acceptable for the purpose of this approximation.
[20] Missing values were interpolated where both adjacent values were provided (12 observations). The South Korean time series, blank until 2001, was completed by assuming a linear budget increase from 1988-2001 to distribute the USD 21.671 m invested since 1988 under the 'Promotion Act for New & Renewable Energy Development' (Kim, 2005). No time lag was used (Griliches, 1990; Hall et al., 1986).

input factors in the case of wind turbines (IMF, 2010) (IRON_PR). To control for the industry knowledge base, two domestic knowledge stocks were constructed: one consisting of domestic wind power patents (KN_STOCK)[22] and one consisting of domestic patents in related technological fields (REL_KN_STOCK).[23] Both stocks were constructed using the patents' publication year with a vintage factor of 0.9. To consider effects that variations in market size may have on the incentives to innovate, we included total annual electricity production (IEA, 2010g) (MARKET_SIZE; in GWh) in our model. We also controlled for changes in patent law and the propensity to patent in a country by using the total number of patent families in a country across all technological fields (PROPENSITY_PAT). Lastly, a ratio of the patents filed in t=1…5 to those filed in t=0 (WINDOW) is included to control for the effect that the number of subsequent filings increases the number of citations the average patent receives.

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[21] While the Kyoto Protocol has not yet been ratified by all countries in our panel (e.g., the US), we assume that its adoption led to a change in the global institutional environment and innovators started anticipating more stringent future policies.

[22] The stock was computed using patents sorted by the year they were published (publication year), not the year they were filed (application year). Only domestic patents were used based on Braun et al.'s (2010) finding that they have a more significant impact.

[23] The corresponding search was based on a list of IPC subclasses compiled by Braun et al. (2010), which was extended by the IPC subclasses used for this work's patent search. The wind power patents were excluded from the results.

Table 1: Descriptive statistics for model variables, period 1978-2002

	Unit	N	Mean	Min	Max	StDev.	Sum
Dependent variables							
Patents	[-]	375	14.79	0	325	30.71	5,546
Patents (≥1 citation)	[-]	375	6.82	0	110	15.10	2,558
Patents (≥5 citations)	[-]	375	1.81	0	40	5.20	679
Patents (≥2 countries)	[-]	375	2.99	0	65	6.55	1,123
Determinants							
DOM_CAPACITY	[MW/a]	375	74.20	0	3247	293.2	27,826
DOM_CAPACITY_CUM	[MW]	375	328,33	0	12,022	1,068	-
FOR_CAPACITY	[MW/a]	375	1,156	0	6,961	1,829	-
FOR_CAPACITY_CUM	[MW]	375	4,597	0	27,812	6,530	-
SUBS_PAID	[m USD]	375	37.95	0	769.2	101.2	14,232
FOR_SUBS_PAID	[m USD]	375	531.3	0	2,254	512.9	-
Control variables							
R&D	[m USD]	356	9.34	0	160	17.3	3,335
KN_STOCK	[-]	375	144	0	684	112	-
REL_KN_STOCK	[-]	375	12,099	0	64,150	9572	-
OIL_PR	[USD/Barrel]	375	38.8	15.4	85.5	20.0	-
ELECTR_PR	[USD c./kWh]	359	10.6	2.37	36.6	5.53	-
MARKET_SIZE	[TWh]	375	428	18	3,892	724	-
PROPENSITY_PAT	[-]	375	66,361	666	558,695	1248	-
WINDOW	[-]	375	6.57	3.26	11.9	2.76	-
IRON_PR	[USD/ton]	375	51.24	35.11	82.08	13.69	-

Further unobserved heterogeneity between countries is controlled for by using a model with country-fixed effects. Time-specific effects are addressed by a time trend variable. Table 1 presents descriptive statistics for the independent variables, determinants and control variables.

4.3 Model specification

The Poisson model and the negative binomial model (NB) are common approaches to regressing count data variables (Hausman et al., 1984). Due to over-dispersion of our data (see Table 1), we used the NB for the standard specification. Whenever the Vuong-test indicated better fitness, results for a zero-inflated negative binomial model (ZINB) are reported as marked in the results tables. To model the period-specific influence of demand-pull policies, we included additional variables. First, we used a dummy (PRE_1990), which is 1 until 1989 and 0 thereafter to proxy the era of competing paradigms and the era of a dominant paradigm. We then constructed interaction terms as the product of the dummy and the demand-pull policy variables. These interaction terms allow us to estimate the difference in slope of the effect of policy on patent counts in the two life-cycle stages. The values of the interaction terms are equal to the normal capacity variables prior to 1990 and 0 in all other years; i.e., the coefficients of the interaction terms indicate the absolute difference in slope between the two time periods, while their signs indicate whether the effect of policy was stronger in the era of competing paradigms (positive sign) or in the era of a dominant paradigm (negative sign): The resulting equation for regressing the number of patent filings Y_{it} in country i and year t is the following (here using marginal capacity variables):

$$X_{it}{}^{T}\beta = \beta_0 + \beta_1 \cdot \log(DOM\_CAPACITY_{it}) + \beta_2 \cdot \log(FOR\_CAPACITY_{it}) + \beta_3 \cdot PRE_{1990} + \beta_4 \cdot \log(DOM\_CAPACITY_{it}) \cdot PRE_{1990} + \beta_5 \cdot \log(FOR\_CAPACITY_{it}) \cdot PRE_{1990} + \sum_{j=1}^{n} C^T \cdot \beta_c + \alpha_i$$

The logarithm is taken for all independent variables except the relative factor prices. C is the vector of control variables, β_c the corresponding vector of parameters, and α_i are the country-fixed effects. Since autocorrelation and heteroskedasticity are present in our data, we report results estimated using heteroskedasticity- and autocorrelation-consistent (HAC) standard errors.

5 Results

In this section we first present the results of the econometric hypothesis test. This analysis covers the entire panel and compares the period-specific influence of demand-pull policies on innovation with the help of interaction terms (models A1-A4). In a second step we separately explore the absolute effect of demand-pull policies on innovation in each life-cycle phase by conducting individual econometric analyses for each phase (models B1-B4) without the interaction effects. In addition, we report results for a variety of robustness tests (models C1-C8, detailed results in Appendix B.3).

5.1 Econometric hypothesis test

The regression results for the hypothesis test are shown in Table 2.[24] In model A1 marginal capacity variables are included while model A2 contains cumulative capacity variables. Models A3 and A4, in addition, include a time trend variable. We also present models excluding the time trend since it introduces multicollinearity to the model (see Appendix B.1). As indicated by the Akaike Information Criterion (AIC), all models A1-A4 exhibit a better fit than models that do not include

[24] After having tested for bivariate Pearson correlation, we included all but one control variable in the final model specifications. The iron ore price was excluded, as it is highly correlated with the foreign capacity variables. Appendix B.1 shows the correlation matrix for the independent variables used in the final model specifications.

the life-cycle stage dummy and the interaction terms or a model that exclusively contains the control variables (see Appendix Table B.2). This underscores the explanatory power of the determinants and the necessity to relax the implicit assumption that innovation effects of demand-pull policies are constant over time.

Table 2: Regression results, period 1978 – 2002

	Model A1	**Model A2**	**Model A3**	**Model A4**
Determinants				
DOM_CAPACITY	0.077* (0.031)		0.067* (0.033)	
FOR_CAPACITY	0.432*** (0.089)		0.315* (0.157)	
DOM_CAPACITY_CUM		0.150*** (0.035)		0.090* (0.042)
FOR_CAPACITY_CUM		0.352*** (0.105)		-0.013 (0.197)
PRE_1990 (dummy)	3.787*** (0.568)	4.866*** (0.816)	3.554*** (0.569)	3.254** (1.072)
INTERACT_TERM (DOM)	-0.133* (0.061)	-0.170*** (0.038)	-0.143** (0.052)	-0.157***(0.039)
INTERACT_TERM (FOR)	-0.665*** (0.093)	-0.583*** (0.100)	-0.590*** (0.117)	-0.336* (0.145)
Control variables				
R&D	0.155† (0.082)	0.178* (0.071)	0.160* (0.072)	0.197** (0.067)
KYOTO (dummy)	0.368† (0.216)	0.488* (0.193)	0.381† (0.203)	0.453* (0.181)
ELECTR_PR	-0.025 (0.031)	-0.025 (0.024)	-0.017† (0.031)	-0.005 (0.026)
ELECTR_MARKET_SIZE	0.420 (0.764)	0.762 (0.545)	0.383* (0.604)	0.544 (0.542)
OIL_PR	0.005 (0.003)	0.003 (0.003)	0.007† (0.004)	0.005 (0.004)
KN_STOCK	0.152 (0.162)	0.228* (0.104)	0.126 (0.131)	0.178† (0.106)
REL_KN_STOCK	0.116 (0.187)	0.134 (0.150)	0.132 (0.163)	0.149 (0.150)
PROPENSITY_PAT	0.350 (0.263)	-0.412† (0.249)	-0.405 (0.266)	-0.439† (0.260)
WINDOW	-0.345 (0.232)	-0.159 (0.230)	-0.332 (0.231)	-0.335 (0.232)
TREND			0.044 (0.053)	0.126* (0.060)
Country fixed effects	Yes	Yes	Yes	Yes
Model Fitness				
AIC	1276	1269	1277	1272

Notes: Regression results for zero-inflated negative binomial model; HAC standard errors in parentheses (full period, N=344); † $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

The significantly positive coefficients of the marginal and cumulative capacity variables in models A1-A4 indicate a generally positive impact of demand-pull policies on innovation. Only in model A4 do we find no significance for the influence of foreign cumulative capacity. This confirms results presented in prior studies on the positive effects of demand-pull policies on innovation. Interestingly, two further findings emerge. First, proxies for both marginal and cumulative demand-pull policies positively correlate with innovation counts. That is, effects of learning-by-doing and learning-by-searching (presumably reflected in marginal capacity variables) as well as learning-by-interacting (cumulative capacity variables) seem to have played an important role in the case of wind power technology. This is consistent with qualitative accounts of the development of wind power (Garud and Karnøe, 2003; Hendry and Harborne, 2011; Karnøe, 1993). Second, domestic as well as foreign policy support are drivers of innovation, suggesting the spillover of innovation incentives from demand-pull policy funding across national boundaries. This, too, is consistent with previous studies (Dechezleprêtre and Glachant, 2011) but raises important questions in terms of industrial policy, not least in the context of international climate agreements.

To test our hypothesis we assess the life-cycle stage-specific influence of demand-pull policies by scrutinizing the coefficients of the interaction terms (i.e., the product of the life-cycle stage dummy and the respective demand-pull policy variable). Strikingly, in all models the coefficients of the interaction terms are significantly negative. The negative sign of the coefficients of the interaction terms (which are equivalent to the capacity variables prior to 1990 and 0 in all other years), implies that the slope of the innovation effect of the demand-pull policy variables was smaller before 1990. Therefore, unexpectedly, we find indications that the positive innovation effect of demand-pull policies is *weaker* in the era of competing paradigms (ante 1990) than in the era of a dominant paradigm (from 1990 onwards). Hence, we do not find support for our hypothesis.

Still, our results appear consistent with regard to the 'pure' effect of diversity, as outlined in section 2.1. The coefficient of the life-cycle stage dummy itself exhibits a significantly positive sign across all models. This finding confirms that diversity appeared to have had, ceteris paribus, a positive effect on innovation,

Among the control variables only the coefficients of public R&D funding and the Kyoto dummy are positive and significant or weakly significant in all models. This confirms the observation that innovation in wind power was – throughout its history – mainly driven by policy support rather than pure market forces (e.g., Sawin, 2001). While the knowledge stock in prior studies typically has a significant positive sign, notably only two out of four model specifications yield this result (in the case of model A4 only at the 10% level). For all other significant variables at the 5% level, the coefficients exhibit the expected signs.

We conducted various robustness tests, which we exemplify with models using cumulative capacity variables for reasons of brevity. They are presented in Appendix B.3 (models C1-C8). The models comprise an alternative life-cycle phase transition in 1987 (when the California Wind Rush ended), different regression model types (Poisson and negative binomial), policy support (monetarized variables), as well as alternative operationalizations of innovation (all patents, with ≥5 citations, filed in ≥2 countries and triadic patents[25]). The results show almost no sensitivity to these alternative specifications and in all cases the hypothesis is *not* supported. Accordingly, we

[25] Patents filed in the U.S., the European patent office, and either China or Japan.

conclude that, surprisingly, in the case of wind power demand-pull policies triggered more innovation in the era of a dominant paradigm than in the era of competing paradigms.

5.2 Exploring the absolute effect of demand-pull policies on innovation in different life-cycle stages

The negative sign of the interaction term coefficients found in the models A1-A4 implies two contradictory effects in the early period: on the one hand a positive effect of demand-pull policies in general, which is on the other hand partly counterbalanced by an effect specific to the era of competing paradigms. Since the analyses in section 5.1 do not provide insights on the balance of the two, i.e., on the *absolute* innovation effect of demand-pull policies in specific life-cycle stages, we scrutinized this absolute effect by dividing the observations into two subsamples for the periods 1978-1989 and 1990-2002. The results are reported in Table 3. Models B1 and B2 refer to the earlier period and include marginal and cumulative demand-pull policy variables, respectively. These specifications are also run for the period 1990-2002 (models B3 and B4).

Table 3: Regression results, periods 1978 - 1989 and 1990 – 2002

	Model B1	**Model B2**	**Model B3**	**Model B4**
Period	1978-1989	1978-1989	1990-2002	1990-2002
Determinants				
DOM_CAPACITY	-0.104** (0.035)		0.013(0.041)	
FOR_CAPACITY	-0.047 (0.047)		0.315** (0.113)	
DOM_CAPACITY_CUM		-0.110*** (0.031)		0.172** (0.063)
FOR_CAPACITY_CUM		0.030 (0.050)		0.112 (0.175)
Control variables				
R&D	0.058 (0.106)	0.023 (0.107)	0.023 (0.076)	0.053 (0.080)
KYOTO (dummy)			0.221 (0.206)	0.210 (0.196)
ELECTR_PR	-0.048 (0.030)	-0.066* (0.031)	-0.032(0.051)	-0.051 (0.054)
ELECTR_MARKET_SIZE	-3.153** (1.032)	-2.932** (1.122)	0.218 (0.660)	0.325 (0.696)
OIL_PR	0.001 (0.004)	0.002 (0.003)	-0.005 (0.007)	-0.005 (0.008)
KN_STOCK	-0.037 (0.137)	-0.151 (0.159)	0.793*** (0.177)	0.465* (0.231)
REL_KN_STOCK	0.225 (0.184)	0.215 (0.210)	0.110 (0.381)	0.532 (0.432)
PROPENSITY_PAT	-0.447 (0.457)	-0.387 (0.584)	0.524 (0.445)	0.572 (0.487)
WINDOW	-0.563 (0.294)	-0.694** (0.252)	-0.317 (0.274)	-0.354 (0.321)
Fixed effects	Countries	Countries	Countries	Countries
Model Fitness				
AIC	467	467	752	751

Notes: Regression results for zero-inflated negative binomial model; HAC standard errors in parentheses (full period, N=344); † $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Intriguingly, the results suggest that demand-pull policies have had a negative effect on innovation in wind power in the era of competing paradigms. Models B1 and B2 both yield significantly negative coefficients, though only for the domestic capacity variables. Since the effect of demand-pull policies on learning mechanisms that are endogenous to deployment can hardly be negative, the negative effect appears to have had its origin in diminished investments in R&D. Hence the results suggest that in the era of competing paradigms, demand-pull policies appear to have triggered effects that either disincentivized R&D investments in general or worsened economic conditions for those firms willing to invest in R&D – as proposed by Nemet (2009).
During the era of a dominant paradigm - as expected - the effect of demand-pull policies on innovation becomes clearly positive. Although models B3 and B4 are not consistent regarding the influence of domestic vs. foreign capacity, both yield significantly positive coefficients for one capacity variable. These results are robust if an alternative life-cycle phase transition in 1987 is chosen (see Appendix B.4).

Regarding control variables, it is worthwhile noting that the knowledge stock variable does not exhibit a significant influence in models relating to the era of competing paradigms (B1 and B2). Two effects could have hindered the build-up and exploitation of knowledge stocks during this period. First, research projects in the field of large-scale turbines often did not rely on experience from earlier projects (Heymann, 1998). Second, the 'small Danish' design was not based on formal development processes (Karnøe, 1993). However, these effects do not seem to exist anymore during the era of a dominant paradigm as – in line with earlier studies – the impact of the knowledge stock on innovation becomes significantly positive (models B3 and B4).

In sum, the analyses of the subsamples yield a negative impact of demand-pull policies on innovation in the era of competing paradigms whereas in the era of a dominant paradigm the effect is positive. This finding is consistent with the results presented in 5.1 and again does not support our initial hypothesis. It also further underscores the importance of differentiating the effects of demand-pull policies by life-cycle phase.

6 Discussion

Given the magnitude of technical change required in the field of clean technologies, it is crucial to better understand the determinants of innovation. Our analysis of the case of wind power suggests that there is not a single, time-invariant causal effect at work between demand-pull policies and innovation. Rather, the life-cycle stage of the technology appears to have been an important moderator of the relationship between demand-pull policies and innovation. More specifically, we find that the impact of demand-pull policies on innovation in the era of competing paradigms is weaker than in the era of a dominant paradigm; our regression results even hint at a negative effect of demand-pull policies on innovation in the era of competing paradigms, a finding that appears worthwhile to address in future theoretical work in this field. Below, we first discuss possible explanations for this unexpected finding. Subsequently, we explore how to translate our findings into implications for technology policy. Finally, we discuss limitations of this study and suggest avenues for future research that appear suitable to address the transferability of findings and policy recommendations.

6.1 A potential 'selection' effect of demand-pull policies

We found the innovation effect of demand-pull policies to be less straightforward – for some models in fact even negative - in the era of competing paradigms than in the period thereafter. In the following, after discussing a set of possible explanations, we argue that demand-pull policies might have triggered 'selection' mechanisms curtailing diversity in the industry and inhibiting innovation.

One could argue that the observation of a weaker innovation effect of demand-pull policies in the era of competing paradigms was due to measurement problems. In this period the 'learning' triggered by demand-pull policies might be underestimated if measured based on patent data. In contrast to other paradigms, formal R&D, which typically translates into patent activity, did not play a major role in the case of the 'Small Danish' paradigm until the second part of the 1980s (Hendry and Harborne, 2011; Karnøe, 1990). Another explanation could be that, innovators – particularly in the US – hardly exploited the existing knowledge stock. US engineers in the field of wind power "barely wait[ed] for the results of one project before moving on to the next" (Sawin, 2001: 141). In the same line of argument, Heymann (1998: 667) states that especially large-scale turbine development was marked by "[r]esearch projects [which] were rarely built on experience from preceding projects". [26]

However, these factors are not able to explain more than just a weaker effect of demand-pull policies during the era of competing paradigms. Since we also find evidence for a negative innovation effect of demand-pull policies in this period, the question arises how demand-pull policies might lead to a *reduction* of learning and innovation. Learning-by-doing and by interacting are endogenous to turbine production and power generation, and it can be reasonably assumed that the variables that we measure cover most, if not all, of the deployment activity in the period. The way we approximate learning-by-searching, however, seems less comprehensive: We measured public R&D and assumed private R&D to occur proportionally and simultaneously – and thus to be measured by turbine sales. This approximation is bound not to include all investments in private R&D. The observed decrease in innovation might thus be caused by decreased investment in private R&D, or decreased success of these investments, in times of strong demand-pull policies.

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[26] Note that this is consistent with our finding in the econometric analysis that the knowledge stock variable has no significant influence on innovation during the era of competing paradigms.

There are two plausible mechanisms with effects in this direction. First, Nemet (2009) proposes that the strong growth of the wind power market in California during the mid 1980s might have created disincentives for the development of new turbine concepts. Instead of 'exploring' new designs by investing in long-term R&D projects, industry participants focused on the 'exploitation' of existing designs. For example, "[at] US Windpower [a turbine manufacturer], new product development efforts came to a standstill" (Garud and Karnøe, 2003: 287) in the early 1980s. However, in other markets such as Denmark there is no evidence for R&D disincentives created through demand-pull policies, and substantial R&D investments accompanied the demonstration projects in the large-scale paradigms throughout their existence.

The second way in which demand-pull policies might have led to a reduction of innovative output of private R&D is related to the decreasing returns to R&D. While we assumed diversity to be exogenous, it can be argued that diversity is no discrete state that moderates the relationship between demand-pull policies and innovation as suggested in our model (see Figure 1), but rather a continuous variable that mediates it. Theory suggests that the emergence of a dominant paradigm is linked to both technological and non-technological dynamics (see Murmann and Frenken, 2006 for an overview), some of which have been related to increased diffusion of certain alternatives (e.g., David, 1985). Qualitative accounts of the case of wind power indicate that the emergence of the 'Small Danish' paradigm and the contraction of the others were, at least partly, due to increasing returns to production. In the early years of the markets in California and elsewhere, wind farm developers and governments had no clear preferences regarding which type of turbine to chose. When the small Danish firms emerged as the preferred suppliers, it was less due to a clearly superior design but more due to field experience in the home market that their turbines were more reliable (e.g., Karnoe 1993) – indicating policy-induced increasing returns. This advantage may have been irreversible, since competing designs were obviously not able to catch up as Danish manufacturers scaled up production and gained experience and (policy-induced) 'learning-by-doing' and 'learning-by-using' further increased the competitiveness of their small-scale designs. That is, demand-pull policies might have increasingly exerted 'selective' pressure on the competing paradigms, making diversity an endogenous factor in our model. If we assume that the decrease in private R&D activities in the other paradigms was not fully compensated by an increase in private R&D in the 'Small Danish' paradigm (and/or assume decreasing returns to R&D), this effect is able to explain the negative effect of demand-pull policies on innovation in the era of competing paradigms.

In summary, we have discussed reasons why we find an innovation effect of demand-pull policies that is weaker (or even opposed) during the era of competing paradigms compared to that during the era of a dominant paradigm. All these effects are likely to have affected our results; yet only the 'selection effect' of demand-pull policies appears capable of explaining why demand-pull policies at times might have a negative impact on innovation. The 'selection' and the learning induced by demand-pull policies are two antagonistic effects in terms of innovation. Yet it is important to be aware that 'selection' is not per-se inefficient; it also generates positive standardization effects such as economies of scale and externalities by allowing supplier specialization, standardized testing and licensing procedures, facilitating employee training, etc. Therefore, considering the trade-off between standardization and diversity is crucial (David and Rothwell, 1996; Stirling, 2007; Tassey, 2000; Van den Bergh, 2008) to derive policy implications.

6.2 Policy implications

Our findings for the case of wind power indicate that foreign as well as domestic demand-pull policies trigger innovation as soon as a dominant paradigm has emerged. Hence demand-pull policies appear to be conducive for the urgently needed innovation in the field of clean technologies. However, our results also suggest that during the era of competing paradigms – at times of high diversity – this innovation effect is weaker or even negative. If we assume that demand-pull policies do not only induce learning but also reduce diversity through selection processes, then the policymaker has to manage a trade-off when applying demand-pull policies: On the upside, such policies create innovation through learning in those paradigms that are able to capitalize on the demand created by the policies, and standardization may entail positive externalities. On the downside, the reduction of diversity cuts off possibly promising avenues for innovation through premature technological lock-ins (Arthur, 1989). Such a trade-off is by definition technology-specific, not only because it is path-dependent, but also because the effects of diversity and standardization can be expected to be highly technology-specific. In view of the increasing prominence of demand-pull policies for the promotion of clean energy technologies, further research on the relationship between demand-pull policies and diversity is necessary, as is research on the detailed mechanisms that link diversity and innovation. It is particularly urgent in order to provide guidance for policy support in technological fields naturally prone to standardization effects, such as smart grids or interfaces for charging electric vehicles.

An active management of this trade-off would require significant understanding of complex technological processes. Policymakers would need to gain transparency on the 'option value' of diversity to derive sound policy interventions. This 'option value' is high in the case of high uncertainty about the performance and cost potentials of different technologies. Policymakers could make use of Stirling's framework (1998, 2007) to assess diversity in terms of balance, disparity and variety. Moreover, leveraging the insights of industry experts might allow policymakers to estimate how uncertain the probability of success is for specific paradigms.

In case the 'option value' is high *before* a dominant paradigm has emerged policymakers would need to apply demand-pull policies very cautiously. Given the dynamic, complex, and decentralized evolution of clean technologies, demand-pull policy schemes in general need to be continuously improved based on experience. Therefore, policymakers should ensure that such policies can be flexibly adapted (Metcalfe 1994). Adaptation mechanisms could, for example, be directly integrated in laws, thus eliminating time lags caused by long amendment processes. Otherwise, positive standardization effects and the innovation created through policy-induced learning could be partly or fully offset by premature 'lock-ins'. Such lock-ins would then increase the risk that ultimately the 'best' paradigm does not emerge as the dominant one. To mitigate the 'selection' effect, investments in demand-pull policies would have to be limited and policymakers could make use of demand-pull policies that do not automatically discriminate alternatives based on economic criteria, such as public procurement, or R&D policy funding that maintains and promotes diversity.

After a dominant paradigm has emerged, the 'option value' of diversity is low. In this case demand-pull policies are well suited to drive innovation. Nevertheless, policymakers should be aware of external shocks, such as breakthrough innovations, which could initiate new paradigms and thus lead to an increase in diversity and make it necessary to adapt policies.

6.3 Limitations and future research

We conclude this paper by pointing out four important avenues for further research, which at the same time reflect the limitations of this work. First, given the indications that demand-pull policies could exert 'selective' pressures, it is intriguing to analyze the effect of demand-pull policies on diversity. To do so a more continuous measure of diversity is needed and a mediator instead of a moderator approach should be chosen. More specifically, scholars could evaluate which selection mechanisms are triggered by demand-pull policies. Second, a better understanding of policy effects on learning within organizations, e.g., a potential trade-off between learning-by-searching through R&D and generating scale and learning-by-doing through production growth, should receive greater scrutiny. Such actor level learning ultimately determines how policy signals translate into technical change and could be investigated by detailed cross-case analyses of companies. Third, it would be beneficial to replicate this study for additional technologies. Besides adding robustness to our findings, this would allow an analysis of the extent to which technology characteristics moderate the relationship between demand-pull policies and innovation and take into account that learning mechanisms vary between technologies. Fourth, instead of focusing on innovation further studies could enlarge the scope of analysis to technical change. Innovation counts are far from being exhaustive when assessing a technology's competitiveness. Standardization effects, i.e., a reduction in diversity, may also be a driver of technical change. To better understand the effect of demand-side policy intervention on technical change it is crucial to shed further light on the trade-off between standardization and diversity. One particular challenge in this context is the differing time lags between the effects of standardization (rather quick) and innovation (rather slow) on technical change.

Appendix A

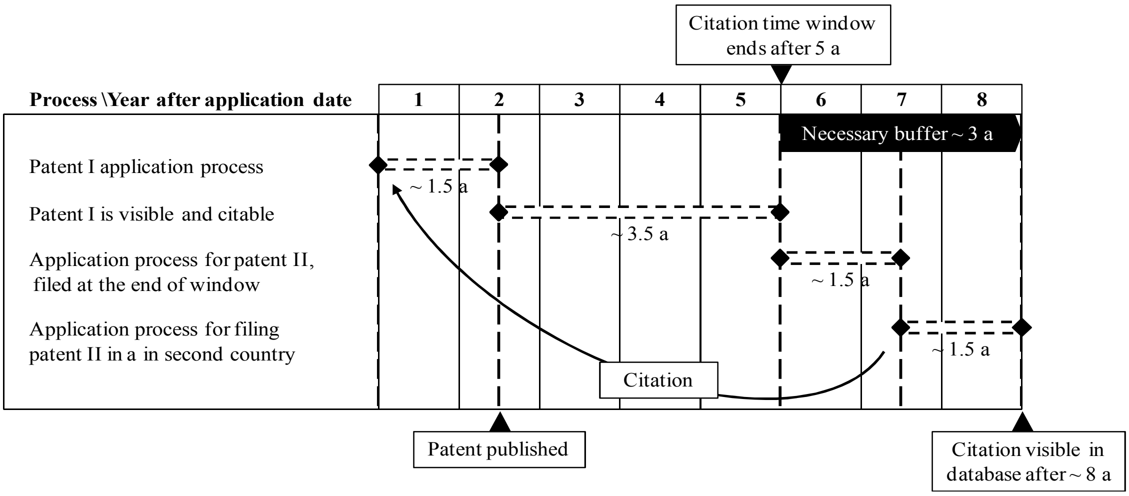

Figure A.1: Citation window time line showing the necessary buffer to include citations made by additional 'family members' of patents published within a 5-year window.

Since the patent application date is used to assign patents to a certain year, it may happen that considerable time passes *after the time window* before all received citations appear in the relevant databases. This makes an additional buffer necessary to ensure the data are comparable. Figure A1 depicts this using a time line of the 5-year citation window. It reads as follows: On average, approximately 18 months after the application date a patent is granted and published. Every time an inventor in the following 3.5 years files an invention citing this patent, its 'citation count' increments by one. Assume now that just at the end of the fifth year an inventor files a patent describing a similar patent which does not, however, cite the first patent. This patent, too, will need about 18 months to proceed through the examination process, during which the examiner does not include any citation changes. The inventor then decides to sign the patent in a second patent office, where the local examiner (after another 18 months) *changes* the proposed citations and includes a reference to the first patent.[27] Since patent families are counted as one document, this citation will now be counted as belonging to the patent filed in the fifth year of the citation time window, and the citation count of the original patent again increments by one (after about 8 years). In an earlier study (Peters et al., 2011), the extension of the buffer from two to three years resulted in a 15% increase in citations. A further extension by one year yielded only a 4% increase. This leads to the conclusion that 3 years seem to be a reasonable trade-off. An accurately applied citation window therefore requires a buffer of at least 3 years *after* the last year of the window before the time the search is performed. The period of observation for this work is thus restricted to 1978-2002.

[27] The patents cited by different offices depend on domestic law and patent classifications or search procedures specific to the patent office (such as the ECLA classification of the EPO).

Appendix B

Table B.1: Correlation matrix of independent variables, 1978 – 2002

	Independent variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	DOM_CAPACITY	1																	
2	FOR_CAPACITY	0.91 ***	1																
3	DOM_CAPACITY_CUM	0.46 ***	0.53 ***	1															
4	FOR_CAPACITY_CUM	0.44 ***	0.50 ***	0.97 ***	1														
5	DOM_SUBS_PAID	0.88 ***	0.97 ***	0.44 ***	0.41 ***	1													
6	FOR_SUBS_PAID	0.41 ***	0.46 ***	0.93 ***	0.98 ***	0.37 ***	1												
7	PRE_1990 (dummy)	-0.50 ***	-0.58 ***	-0.69 ***	-0.7 ***	-0.49 ***	-0.66 ***	1											
8	PRE_1987 (dummy)	-0.44 ***	-0.51 ***	-0.67 ***	-0.78 ***	-0.44 ***	-0.79 ***	0.78 ***	1										
9	R&D	0.37 ***	0.39 ***	-0.08	-0.09	0.38 ***	-0.09 †	0.05	0.08	1									
10	KYOTO (dummy)	0.55 ***	0.54 ***	0.60 ***	0.50 ***	0.45 ***	0.44 ***	-0.48 ***	-0.38 ***	0	1								
11	ELECTR_PR	-0.39 ***	-0.47 ***	-0.66 ***	-0.76 ***	-0.41 ***	-0.8 ***	0.69 ***	0.83 ***	0.10 †	-0.35 ***	1							
12	ELECTR_MARKET_SIZE	-0.24 ***	-0.31 ***	-0.24 ***	-0.25 ***	-0.26 ***	-0.25 ***	0.34 ***	0.34 ***	-0.17 **	-0.23 ***	0.31 ***	1						
13	OIL_PR	0.17 **	0.26 ***	0.11 *	0.10 *	0.25 ***	0.11 *	-0.16 **	-0.16 **	0.43 ***	0.12 *	-0.15 **	-0.07	1					
14	KN_STOCK	0.51 ***	0.56 ***	0.60 ***	0.63 ***	0.50 ***	0.63 ***	-0.41 ***	-0.49 ***	0.41 ***	0.28 ***	-0.48 ***	0.02	0.32 ***	1				
15	REL_KN_STOCK	0.38 ***	0.41 ***	0.50 ***	0.51 ***	0.35 ***	0.49 ***	-0.38 ***	-0.41 ***	0.32 ***	0.30 ***	-0.38 ***	-0.07	0.38 ***	0.77 ***	1			
16	PROPENSITY_PAT	0.19 ***	0.23 ***	0.11 *	0.10 †	0.21 ***	0.10 †	-0.14 **	-0.13 *	0.38 ***	0.14 **	-0.13 *	-0.09 †	0.77 ***	0.22 ***	0.42 ***	1		
17	WINDOW	0.46 ***	0.54 ***	0.61 ***	0.61 ***	0.45 ***	0.58 ***	-0.87 ***	-0.76 ***	-0.07	0.46 ***	-0.72 ***	-0.35 ***	0.15 **	0.34 ***	0.33 ***	0.14 **	1	
18	TREND	0.60 ***	0.67 ***	0.90 ***	0.89 ***	0.57 ***	0.86 ***	-0.87 ***	-0.83 ***	-0.05	0.69 ***	-0.78 ***	-0.35 ***	0.18 ***	0.56 ***	0.49 ***	0.17 **	0.81 ***	1

† $p < 0.1$ * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table B.2: Regression results, period 1978 – 2002

	Model A5	**Model A6**
Determinants		
DOM_CAPACITY		0.048† (0.025)
FOR_CAPACITY		-0.082† (0.045)
Control variables		
R&D	0.261*** (0.071)	0.237** (0.074)
KYOTO (dummy)	1.459*** (0.184)	1.410*** (0.209)
ELECTR_PR	-0.073* (0.035)	-0.055 (0.034)
ELECTR_MARKET_SIZE	1.396*** (0.416)	1.529*** (0.451)
OIL_PR	0.013** (0.004)	0.013** (0.004)
KN_STOCK	-0.203* (0.098)	-0.114 (0.119)
REL_KN_STOCK	0.286† (0.168)	0.234 (0.184)
PROPENSITY_PAT	0.733** (0.226)	-0.465 (0.285)
WINDOW	-0.028 (0.240)	0.011 (0.234)
TREND		
Country fixed effects	Yes	Yes
Model Fitness		
AIC	1325	1323

Notes: Regression results for zero-inflated negative binomial model; HAC standard errors in parentheses (full period, N=344);† $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Table B.3: Alternative model specifications for robustness tests

	Model C1	Model C2	Model C3	Model C4	Model C5	Model C6	Model C7	Model C8
Dependent variable	≥1 citation	All patents	≥5 citations	filed in ≥2 countries	Triad patents	≥1 citation	≥1 citation	≥1 citation
Model	ZINB	ZINB	ZINB	ZINB	ZINB	NB	Poisson	ZINB
Determinants								
DOM_CAPACITY_CUM	0.153** (0.028)	0.075** (0.025)	0.274** (0.084)	0.139** (0.050)	0.196* (0.080)	0.113*** (0.032)	0.134*** (0.024)	
FOR_CAPACITY_CUM	0.264** (0.081)	0.273*** (0.081)	0.512*** (0.158)	0.241* (0.119)	0.282 (0.215)	0.276** (0.091)	0.327*** (0.070)	
DOM_SUBS_PAID								0.200*** (0.057)
FOR_SUBS_PAID								0.474** (0.160)
DUMMY_PRE_1990		3.964*** (0.659)	6.667*** (1.417)	3.657*** (0.954)	3.733† (1.930)	4.547*** (0.730)	4.600*** (0.532)	4.674*** (1.051)
DUMMY_PRE_1987	4.184*** (0.607)							
INTERACT_TERM (DOM)	-0.183*** (0.037)	-0.121*** (0.028)	-0.211* (0.092)	-0.195*** (0.053)	-0.158† (0.088)	-0.124*** (0.036)	-0.149*** (0.028)	-0.306*** (0.062)
INTERACT_TERM (FOR)	-0.506*** (0.077)	-0.460*** (0.085)	-0.965*** (0.186)	-0.453*** (0.117)	-0.518* (0.221)	-0.603*** (0.090)	-0.570*** (0.067)	-0.711*** (0.160)
Control variables								
R&D	0.190** (0.068)	0.148* (0.062)	0.211† (0.115)	0.186* (0.080)	0.271† (0.152)	0.141* (0.061)	0.202*** (0.050)	0.201* (0.082)
KYOTO	0.555** (0.183)	0.391* (0.160)	0.328† (0.248)	0.601** (0.232)	0.422 (0.393)	0.365* (0.162)	0.458*** (0.109)	0.577* (0.228)
ELECTR_PR	-0.021 (0.029)	-0.005 (0.022)	-0.022 (0.077)	-0.039 (0.031)	-0.094 (0.075)	-0.035 (0.023)	-0.045* (0.019)	-0.047** (0.032)
ELECTR_MARKET_SIZE	0.590 (0.583)	0.850** (0.309)	-1.566† (0.898)	0.262 (0.481)	-1.130 (1.105)	0.297 (0.312)	0.511 (0.333)	0.441 (0.471)
OIL_PR	0.002 (0.003)	0.001 (0.003)	-0.006 (0.007)	-0.001 (0.005)	0.002 (0.008)	0.004 (0.003)	0.003 (0.002)	0.003 (0.005)
KN_STOCK	0.258* (0.104)	0.200* (0.088)	0.230 (0.260)	0.299* (0.118)	0.536* (0.234)	0.456*** (0.093)	0.251** (0.077)	0.270* (0.121)
REL_KN_STOCK	0.166 (0.156)	0.022 (0.073)	0.970* (0.443)	-0.062 (0.148)	0.189 (0.392)	0.019 (0.132)	0.208† (0.124)	-0.057 (0.161)
PROPENSITY_PAT	-0.332 (0.253)	0.160 (0.196)	-0.568 (0.643)	0.116 (0.287)	0.410 (0.578)	0.326 (0.207)	-0.310 (0.194)	-0.067 (0.277)
WINDOW	-0.317 (0.186)	-0.487** (0.189)	0.858* (0.419)	-0.516 (0.316)	-1.193* (0.546)	-0.357 (0.212)	-0.223 (0.148)	-0.283 (0.325)
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Model Fitness								
AIC	1270	1839	659	1146	610	1168	1214	1147

Notes: HAC standard errors in parentheses (full period, N=344);† $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table B.4: Regression results, periods 1978 – 1986 and 1987 - 2002

	Model B5	**Model B6**
Period	1978-1986	1987-2002
Determinants		
DOM_CAPACITY	-0.125** (0.040)	0.025 (0.029)
FOR_CAPACITY	-0.099 (0.064)	0.297*** (0.080)
Control variables		
R&D	-0.081** (0.129)	0.092 (0.070)
KYOTO (dummy)		0.310** (0.214)
ELECTR_PR	-0.011† (0.042)	-0.025 (0.041)
ELECTR_MARKET_SIZE	-4.217* (2.373)	-0.188 (0.552)
OIL_PR	0.004 (0.005)	-0.005 (0.008)
KN_STOCK	0.041 (0.165)	0.856*** (0.159)
REL_KN_STOCK	0.278 (0.207)	0.105 (0.407)
PROPENSITY_PAT	0.430 (0.714)	0.213 (0.339)
WINDOW	-0.711 (0.461)	-0.300 (0.191)
Fixed effects	Countries	Countries
Model Fitness		
AIC	363	864

Notes: Regression results for zero-inflated negative binomial model; HAC standard errors in parentheses (full period, N=344);† $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

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PAPER IV

The two Faces of Market Support –
How Deployment Policies Affect
Technological Exploration and Exploitation
in the Solar Photovoltaic Industry

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Abstract

The recent years have seen a strong rise in policies aiming to increase the diffusion of clean energy technologies. While there is general agreement that such deployment policies have been very effective in bringing technologies to the market, it is less understood how these policies affect technological innovation. To shed more light on this important question, we conducted comparative case studies with a global sample of 9 firms producing solar photovoltaic (PV) modules, complemented by in-depth interviews with 16 leading PV industry experts. We propose that, on the one hand, policy-induced market growth serves as an important catalyst for innovative activity as it raises the absolute level of firm investments in technological exploration. On the other hand, however, strong market growth creates an incentive for firms pursuing more mature technologies to concentrate on technological 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 raises the barrier to market entry for less mature technologies. We conclude that, when designing deployment policies, great care should be taken to avoid excess market growth so as to a) not induce strong exploitative behavior of firms and b) reduce the likelihood of 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; Bundesministerium für Umwelt, 2010).

Environmental economics suggests that, besides having a positive effect on diffusion, deployment policies can 'induce' innovation (e.g., Del Río González, 2009). 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 they 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 firms 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 challenges such as climate change call for profound, large-scale technological shifts, such outcomes seem everything but desirable from a policy standpoint. 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 firm characteristics influence the link between deployment policies and firm-level exploration and exploitation.

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 policymakers (section 6). The paper concludes with a description of the study's 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: Environmental economics and quasi-evolutionary approaches to innovation policy.

Environmental economics argues that environmentally benign innovation suffers from a so-called 'double externality problem' since the environmental side-effects of economic activity are not sufficiently reflected in market prices and, in the face of knowledge spillovers, firms may systematically underinvest in innovation (Rennings, 2000). In order to correct for these market failures, environmental economics suggests that policymakers 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). In the literature, this is reflected in the concept of learning curves and the large number of economic models that treat technical change as endogenously (and often exclusively) driven by technology deployment (Clarke et al., 2008).

In quasi-evolutionary approaches, deployment policies are not only seen as a means to correct for externalities in an otherwise efficient market (Metcalfe, 1994; Nill and Kemp, 2009). It is reasoned that policymakers can foster technological learning and may help to break technological lock-ins in which sectors become trapped due to a variety of factors, such as increasing returns to scale or network effects (Malerba, 2009; Unruh, 2000). In this context, 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).

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 a sectoral level, and assume a direct relationship between policy and this variable (Cleff and Rennings, 1999). 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 (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 to invest in exploration as, in the view of a rapidly growing market, organizations might shift their focus from exploration towards exploitation. Such a shift in the relative balance between exploration and exploitation, in turn, may have a significant impact on whether innovations witnessed in an industry are of a rather radical or incremental nature (Malerba, 2009). Malerba (2009) suggests that, in the longer term, a strong focus on exploitation may lead to more incremental innovations and reduced technological diversity within an industry. He infers that policymakers should try to influence the balance between different forms of learning to avoid competence traps, path dependencies and technological lock-ins, which accompany low technological diversity. Therefore, when studying the effect of deployment policies, it appears important to clearly distinguish to which degree deployment policies trigger investments in exploration and exploitation.

2.3 Antecedents of exploration and exploitation

While some anecdotal evidence has been presented that deployment policies may induce firms to focus on exploitation, currently how exactly deployment policies affect exploration and exploitation on an organizational level remains insufficiently understood. 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 a firm's slack resources (e.g., Greve, 2007; Nohria and Gulati, 1996). 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 might 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 endowment of resources and capabilities

(Dosi, 1982). It seems likely that such firm 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, 2008). Besides providing a more fine-grained perspective of the mechanisms linking deployment policies and technological learning, studying the effect of deployment policies on the firm level also allows for the examination of the potentially moderating effects of firm characteristics.

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 as investments in exploration.

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, we furthermore consider firm characteristics which might moderate the effect of deployment policies on corporate investments in technological learning (3).

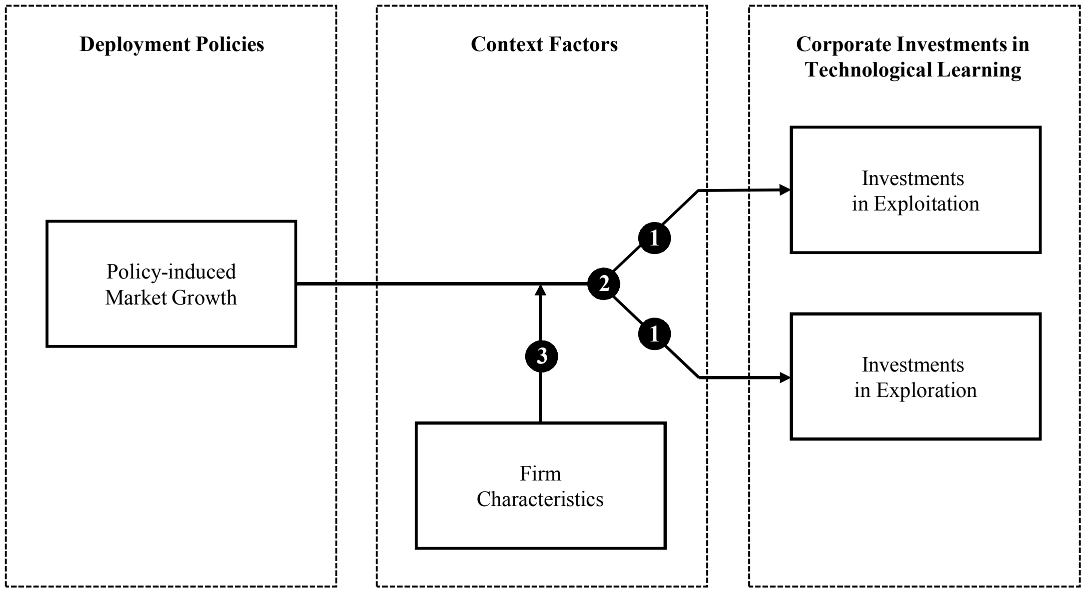

Figure 1: Initial research framework

3 Research case

As our research case we chose producers of solar photovoltaic (PV) modules.[1] The PV sector is very well suited to investigating the effect of deployment policies on corporate investments in technological learning for two reasons. First, markets in the sector are strongly dependent on deployment policies and, second, in the absence of a dominant design for PV modules, investing in both exploration and exploitation bears significant potential for advancing the technology.

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).

[1] 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, Schmidt, 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.

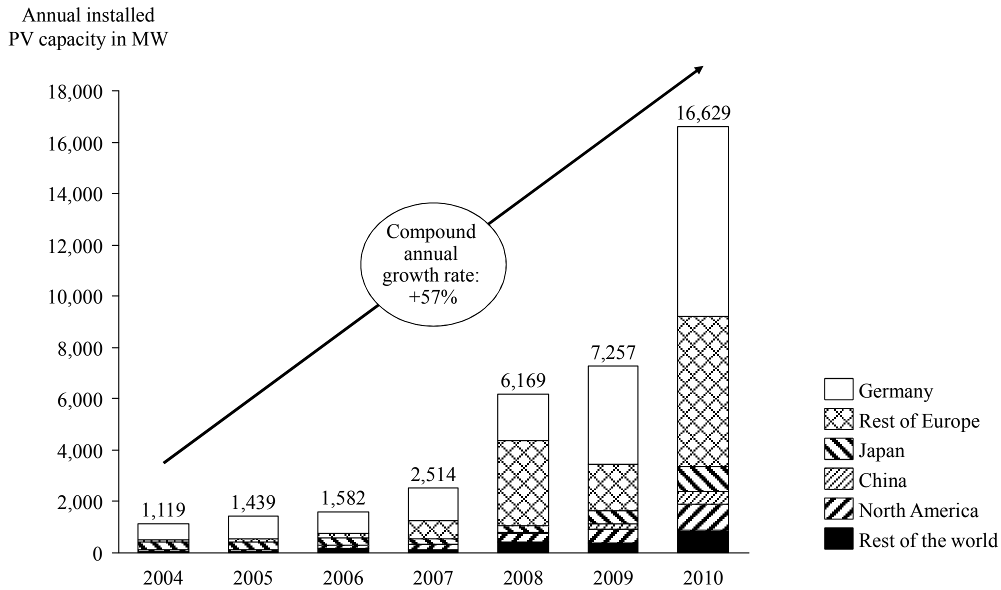

Figure 2: Development of PV markets 2004 to 2010 (data from EPIA, 2011)

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 and assumes the largest proportion of the market with a share of around 86% in 2010. To produce modules based on this technology, 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. 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). In light of these distinct strengths and weaknesses, it currently remains unclear which of the competing PV technologies might become the dominant design. Therefore, on the path towards competitiveness both exploiting the potentials of learning-by-doing and economies of scale as well as exploring alternative technological avenues to benefit from potential cost advantages in the future seem valid options.

Table 2: Overview of PV technologies

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

[1] mc-Si: Mono-crystalline silicon
[2] pc-Si: Poly-crystalline silicon
[3] a-Si/µ-Si: Amorphous/mircromorphous silicon
[4] CIGS: Copper-indium-gallium-selenium
[5] CdTe: Cadmium telluride
[6] CPV: Concentrated photovoltaics
[7] OPV: Organic photovoltaics
[8] Except CPV (○)
[9] 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 firm-level 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 the nature 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 firm-level 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.

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 policymakers, 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 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, Griesshaber, et al., 2011), location was considered an important sampling criterion to account for differences in national deployment policy instruments and a firm's geographic proximity to high-growth markets. Furthermore, we chose to interview firm representatives in companies of different sizes pursuing a wide variety of different PV technologies to reveal potential influences of technology and firm characteristics, such as slack resources, on their reaction to policy incentives.

Table 3: Overview of expert sample

Category	Person	Description
Policymaker	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**									**Sum**
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	
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[2]. Prior to all interviews we systematically scanned analyst reports, newspaper articles, annual reports and company statements for information related to our interviewee. These insights were translated into tailored interview guidelines which we then used as the basis for a semi-structured discussion during the interviews (see Table A.2 in the appendix for a typical interview guide). All interviews typically 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 onwards. 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).

[2] 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.

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 and exploitation. Since the mechanisms linking deployment policies and exploitation are perspicuous, we concentrate on explaining the link between policy-induced market growth and exploration. Absolute levels of investments in explorative learning seem particularly relevant in the case of PV as this technology is still far from competitiveness with no clear dominant design having emerged yet (see section 3). *Second*, we show how policy-induced market growth affects firms' *balance* between exploration and exploitation. Investigating this question on a firm-level, we are able to draw a nuanced picture of the mechanisms, pointing out differences in the effect for firms pursuing more and less mature PV technologies. *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 our study we identified two major causal mechanisms which in the following will be described in greater detail.

First, policy-induced market growth raises an industry's capital resources for exploration through *increased investor interest* (see upper 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). This venture capital, in turn, enabled corporate exploration activities since it "in essence funded R&D of new technologies" (Chief Strategy Officer, Firm H). 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). Figure 3 depicts market growth and US VC funding in solar energy, as an important source of funding for exploration, over time. In line with our interview findings it shows that these two variables seem to follow a similar pattern.

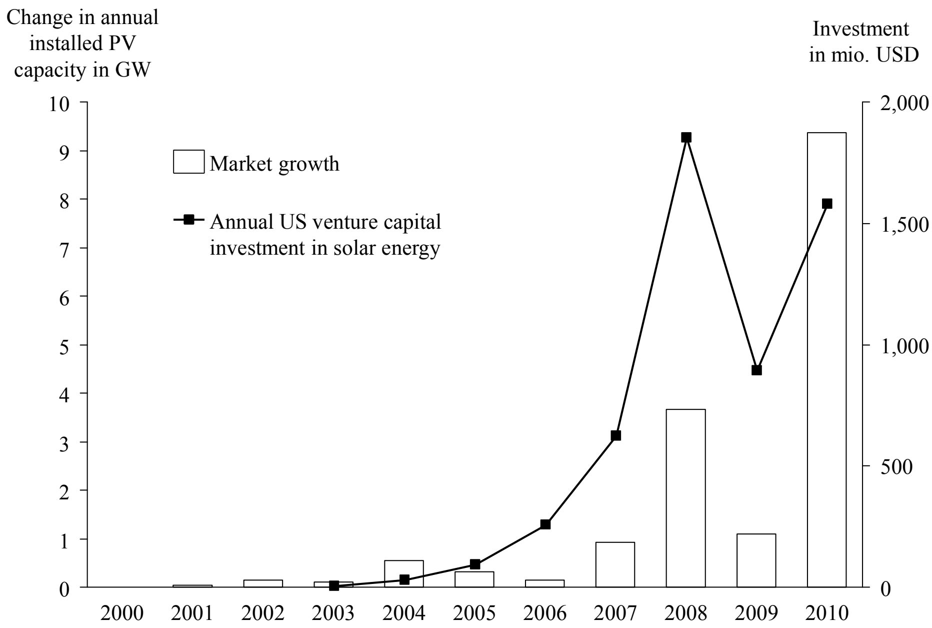

Figure 3: Market growth and US venture capital investments in solar energy (data from EPIA, 2011; Ernst & Young, 2011; PwC, 2009)

Second, our findings confirm previous research which suggests that market growth enables firms possessing commercial products to generate *positive income from exploitation* which is subsequently reinvested in exploration activities (see lower part of Table 5). In the view of strong market growth, companies 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; Schmookler, 1962).

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

Mechanism	Exemplary Quote	Source
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
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

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 firms' exploration investments through elevated investor interest and higher revenues. 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.

During the course of our study it became apparent that the question of whether a company alters its balance between exploration and exploitation as a result of deployment policies cannot be answered unequivocally without considering the company's product technology. In fact, the *technological maturity* of the firm's products, which we operationalize as the *proximity of a company's products to commercialization* (Foxon et al., 2005), emerged as a particularly important moderating factor. Since the effects of deployment policies we observed differ quite significantly depending on this factor, in the following we separately discuss the mechanisms linking deployment policies and technological learning 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

Although R&D investments in the PV sector have continuously grown in absolute terms, the large majority of industry experts we interviewed reported that producers pursuing more mature technologies, such as wafer-based c-Si, had invested comparatively little into R&D relative to sales. For example, Policymaker 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 4 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 decrease 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).

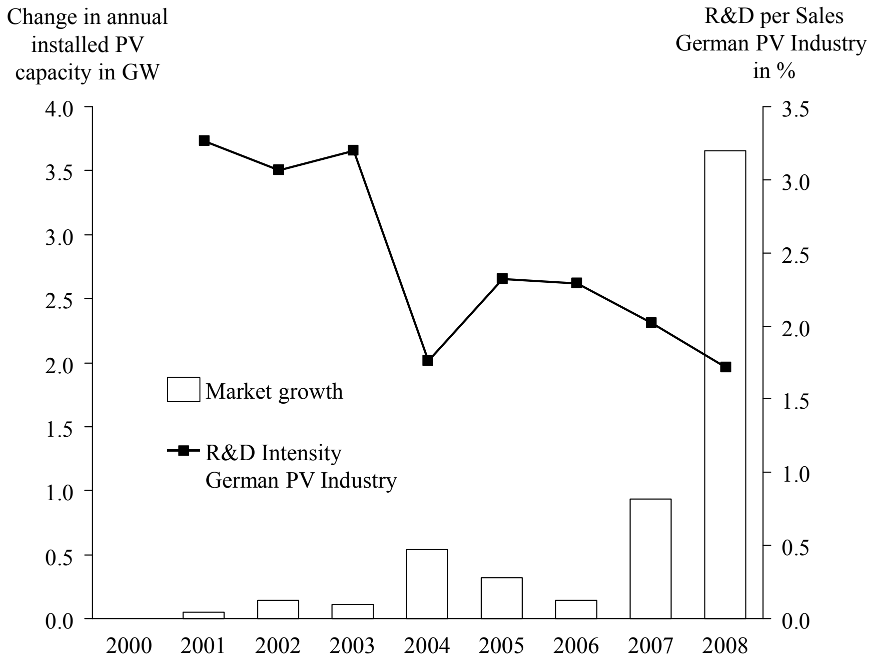

Figure 4: Global market growth and R&D intensity of the German PV industry (data from BSW Solar, 2010; EPIA, 2011, no data available for 2009 and 2010)

During our interviews we found that part of the relatively low investments in explorative learning among firms pursuing more mature technologies may be connected 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 firms' focus on exploitation relative to exploration hinges on the level of policy-induced market growth. 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 two major reasons.

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" (Policymaker 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 lower part of Table 6). When operating in a market with stronger demand and higher margins, firms incur higher opportunity costs for organizational resources which they do not invest in exploitation "because the relative value loss of each unit of unsold product [is] so high" (Firm C, Chief Technology Officer). Interestingly, most of the companies we interviewed reported that there is no direct *financial* trade-off between investments in exploration and exploitation, as "R&D expenses are not remotely on the same scale as production capacity investments" (Firm C, Director Business Development). However, regarding *human resources*, the majority of interviewees confirmed that there is a clear trade-off between exploration and exploitation. Firms stressed that in terms of man-power in times of strong market growth "you are putting all your effort into volume increases" (Firm C, Director Business Development), "R&D was only second priority" (Firm A, Strategy Department) and "people working in technology development were drawn out of R&D and worked on building capacities" (Firm C, Chief Operating Officer). These shifts in organizational focus translate 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 the focus of corporate financial investments in exploitation even though capital resources do not constitute the bottleneck.

In summary, our findings concur with Nemet's (2009) proposition 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 and set strong incentives to use scarce human resources for exploitation. 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.*

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 policymakers 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

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 production 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 firms prohibitively difficult, resulting in a “third valley of death” which “can be extremely difficult to overcome” (Scientist C).

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.*

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 production 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

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.

Outsourcing of Exploration Activities: One may ask whether the changes in the balance of exploration and exploitation we observe are not simply due to systematic trends in outsourcing exploration activities to a reliable partner. In fact, outsourcing R&D activities to equipment manufacturers or public research institutes has been a common theme in the PV industry. However, from our study no clear trend towards outsourcing emerged that could serve as an alternative explanation to the effects of deployment policies described previously. As the President of Firm E reported, rather than outsourcing R&D activities, several companies were trying to integrate tasks previously conducted by equipment suppliers to increase their competitive advantage. Moreover, our findings indicate that in fact equipment manufacturers themselves have been subject to the effects described in propositions I to III. The Director of Business Development of Equipment Manufacturer A pointed out that "[i]n our case, there was huge growth. You need to handle this first before you are able to think about how to develop the technology further."

Factor Prices: 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. The newly built capacities will not only resolve temporary bottlenecks 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 existing literature

Our study contributes to the current literature in two ways. First, we generally concur with the view that policies fostering the deployment of technologies can induce innovation. However, we argue that, in investigating the innovation effect, it is important to distinguish different modes of technological learning, such as exploration and exploitation, as these may be differently triggered by policy-induced demand. Firms generally possess limited organizational resources which they can invest in explorative and exploitative learning at each point in time. In contrast to current theory, we do not observe a strong financial trade-off between these two modes of learning. Nevertheless, we find that high policy-induced market growth reduces exploration pressure and creates a strong incentive to shift scarce human resources from explorative to exploitative activities. Since exploitation is likely to lead to products which are more incremental in nature, our results suggest that the degree to which deployment induces innovation may depend on *how fast* a policy induces a particular level of demand. The widely used methodology of learning curves implies that learning is a function of cumulative demand, irrespective of the speed at which this demand has accumulated over time. According to our findings such a static view may be overly simplistic as it neglects shifts between different forms of learning that occur during periods of high growth, suggesting that in such phases learning may not be a mere function of past deployment volume.

Second, we suggest that research on deployment policies can strongly benefit from a more fine-grained understanding of firm-level factors that moderate the effect of deployment policies. Empirical studies often treat firms as homogenous actors which perceive and react to policies in an equal way. In contrast, our findings imply that particularly the technological maturity of a company's products may have an important influence on the degree to which deployment policies induce firm investments in specific forms of learning. Firms pursuing less mature technologies are not able to reap the benefits of exploitative learning to the same extent as firms pursuing more mature technologies. As a consequence, strong policy-induced market growth increases the risk of a technological lock-in into potentially inferior technologies. In fact, during our interviews we gathered a surprising amount of evidence that point to a looming technological lock-in in the PV industry (see Table A.4 in appendix). Several of the company representatives and experts we interviewed stressed that emerging technologies were intrinsically superior to wafer-based crystalline PV technologies. However, the firms pursuing the latter technologies reported that under existing conditions they could not compete with wafer-based PV and deliberately targeted niche markets such as building integrated PV. Three representatives from firms producing wafer-based PV independently pointed to similarities between the development of the PV industry and that 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 a strong focus on deployment policies may not be well suited to enhancing technological diversity *within these niches* as it favors more advanced technological designs. 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 policymakers

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 raise investments in both explorative and exploitative forms of learning. However, our study implies that when designing deployment policies, policymakers are well advised to avoid inducing excessive market growth. First, when raising the demand for clean energy technologies at a slower rate, policymakers may be able to avoid exploitative firm behavior. As exploitation is likely to lead to more incremental innovations, deployment policies that induce weaker growth may reach a desired level of technological learning at a lower cost than when inducing stronger growth. Second, slower policy-induced market growth can reduce the risk of a premature technological lock-in into inferior technologies. In the case of PV, a lock-in into a particular technology might be particularly critical as it is still uncertain 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.

While, at first glance, the slower diffusion of clean energy technologies may seem undesirable from an ecological point of view, the effect of reducing the rate of diffusion might be more than outbalanced by a higher performance of the technologies diffusing into the market, as companies pursue more explorative innovation and market entrants face lower barriers to entry. Furthermore, inducing slower growth rates might help to reduce problems with public acceptance that result from high annual costs for technology support. Since enduring public acceptance is one of the key requisites for a stable policy scheme, reducing market growth rates may help to avoid sudden collapses of national markets as witnessed in Spain or the Czech Republic for the case of PV.

To counterbalance the potential adverse effects of market growth on technological diversity, besides keeping policy-induced market growth at appropriate levels, policymakers 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, policymakers should complement deployment policies with R&D and venture support. Raising the number of start-ups before the deployment policy is introduced may help to increase the innovation pressure and reduce overly exploitative behavior. Furthermore, using policy instruments such as R&D subsidies or R&D tax credits in parallel to deployment policies can help to set incentives for firms to invest in exploration and reduce the likelihood of a premature technological lock-in.

7 Limitations and future research

This study has some limitations which represent potentially fruitful avenues for future research. First, our research pays only limited attention to the uncertain nature of future policy-induced demand. It can be assumed that investment decisions in firms are, at least partly, taken based on expectations regarding future market development. While these expectations are strongly based on observations of actual growth, they may differ among firms depending on a firm's information, forecasting abilities and cognitive factors. Additionally, apart from concrete policy incentives, expectations regarding future demand may be influenced by policy targets as well as beliefs related to when a technology might achieve a competitive cost structure in the absence of policy support.

Second, 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, 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. Future studies might therefore look at the degree to which technology characteristics moderate the relationship between policy-induced market growth and technological learning as well as technological diversity.

Finally, our research provides initial insights into how deployment policies affect the balance between explorative and exploitative learning. Nevertheless, it remains unclear how these different modes of learning translate into concrete innovative outcomes over time. From the perspective of a policymaker, what is the value of fostering technological variety compared to advancing a technology on an existing trajectory? Further research that also addresses potential feedback loops between policy making and industry dynamics seems necessary to develop targeted, empirically grounded policy recommendations for future deployment policies.

8 Conclusion

Our study contributes to a better understanding of how deployment policies induce technological innovation. Since previous work has studied the effect of deployment policies on more aggregate levels of analysis, we focused on the firm level and investigated the question of how deployment policies affect corporate investments in exploration and exploitation. We suggest that policy-induced market growth leads to an absolute increase in the level of firm investments in exploration as it attracts venture capital investors and raises the firms' financial resources. 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 technologies, an increase in policy-induced market growth reduces the immediate need to invest in longer-term explorative activities and creates a strong incentive to shift scarce human resources from exploration towards exploitation. Firms pursuing less mature 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, policymakers should refrain from inducing excessive market growth in order to avoid causing strong exploitative firm behavior and increasing the risk of technological lock-ins.

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 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: 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.”	Policymaker B

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Annex II – Curriculum Vitae

CURRICULUM VITAE - MICHAEL PETERS

PERSONAL DATA

Address:	Kopernikusstr. 18a, 10245 Berlin, Germany Phone +49 175 318 8902 Mail mpeters@ethz.ch
Date and place of birth:	2nd November 1981, Mainz (Germany)

EDUCATION

01/2009 – 10/2011	Ph.D. student at **ETH Zurich** (Switzerland), Chair of Sustainability and Technology; topic of thesis: The Role of Technology Policy in Fostering Technical Change – Lessons from the Cases of Solar and Wind Power
01/2005 - 09/2006	**WHU – Otto Beisheim School of Management**, Vallendar (Germany); majors: international strategy and communication, corporate finance, international economics; diploma grade: 1.6[1]
06/2004 - 08/2004	Exchange semester at **Indian Institute of Management Ahmedabad** (India); 2nd year MBA program
01/2004 - 05/2004	Exchange semester at **HEC Montréal** (Canada); 3rd year Bachelor program (in French)
10/2002 -12/2003	**WHU – Otto Beisheim School of Management**, Vallendar (Germany), studies in business administration; intermediate diploma grade: 1.9[1]
08/1993 - 06/2001	Elisabeth Langgässer Gymnasium, Alzey (Germany) – A-levels: 1.1[1]; exchange term at Duchess Park High School, Prince George (Canada)

PROFESSIONAL HISTORY

12/2006 – **McKinsey & Company, Munich (Germany)**

Consultant with focus on **strategic projects** in the fields of **climate change** and **renewable energies**, e.g.,

- Assessment of cost and potential of greenhouse gas abatement in Germany, joint study with the Federation of German Industries (BDI)
- Entry strategy into market for Concentrating Solar Power for client active in plant construction
- Growth strategy for technology provider active in PV cell manufacturing

06/2005 - 08/2005 **McKinsey & Company, Munich (Germany)**

Project assignments: Development of a business plan for a luxury fashion label, study about future propulsion technologies in the automotive sector

1 scale: 1 (= best) to 6

09/2004 - 12/2004	**Mercer Management Consulting, Munich (Germany)** Project assignment: Strategic realignment of a major European airport: Simulation of revenue flows within the strategic business unit “Aviation”, coaching of client employees, generation of an employee transfer matrix
05/2003 - 08/2003	**Schott Fiber Optics, Southbridge (USA)** Production Control Department: production planning with MRP-system, preparation of the annual inventory

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COMMUNITY SERVICE

09/2001 - 06/2002	Paramedic (520h education) at the German Red Cross (DRK) in Alzey

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SCHOLARSHIPS

04/2003 - 09/2006	Scholarship holder of the German National Academic Foundation (Studienstiftung des deutschen Volkes)

LANGUAGE AND COMPUTER KNOWLEDGE

German:	Native speaker
English:	Fluent
French:	Fluent
Spanish:	Basic knowledge
	Microsoft Office, Windows XP, Lotus Notes

Zurich, October 31, 2011