Working Paper Sustainability and Innovation
No. S 10/2015

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Impacts of policies on market formation and competitiveness – The case of the PV industry in Germany

Fraunhofer
ISI

Acknowledgment

This paper is part of a research project funded by the German Federal Ministry of Education and Research (BMBF) under the funding label Econ-C-026, whose support we gratefully acknowledge. The author is solely responsible for the contents of this publication.

Abstract

This paper analyzes the impact of German policies promoting PV on industry structures and technological changes in the PV sector. A quantitative analysis is conducted by applying a set of policy variables derived from demand-, supplier- and R&D-focused policies. To depict the industry structure, the production volume in MW of German PV module and cell manufacturers offers a good basis to derive structural variables. Patent applications are used to illustrate technological changes and competitiveness. The approach includes a descriptive as well as a multivariate analysis relying on the operationalization of demand policies and a policy mix. The results underpin the significance of demand policies and a policy mix for market formation and knowledge generation. But they also indicate that policies enhancing PV demand induce growth in PV industries abroad as well, which in turn affects domestic industry structures.

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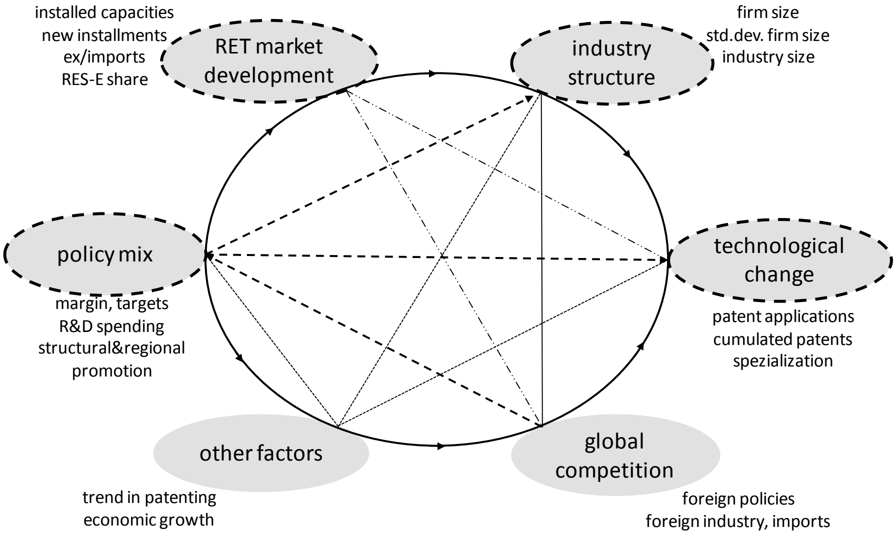
1 Introduction

Since 1990, the share of renewable energy (RE) in the German power generation mix has grown enormously. The FIT (feed-in tariff) scheme in Germany has been very successful in increasing the deployment of renewable energy technologies. This growth has been accompanied or pushed by diverse policies that entail costs as well as benefits at the system-, macro- and micro-economic levels (ISI et al. 2014). Technological changes are regarded as a major positive impact of RE demand-pull and technology-push policies. Especially demand-promoting policies such as the FIT scheme in Germany have contributed to increasing the deployment of renewable power generation technologies (RPGT) and hence, to decreasing technology costs due to learning effects, innovations and economies of scale (Söderholm und Sundqvist (2007), Groba, F. Breitschopf, B. (2013)). In the framework of the BMBF's "Gretchen" project, the impact of policies on the industrial structures and technological changes in solar PV has gained special attention. The research analyzes not only the impacts of single policies, but of a set of policies. In this context, policies are understood as a mix of policy target, demand-pull and technology-push instruments and supplier-focused policies as described in (Breitschopf 2015a). Besides national policies, other factors such as market development, competition and/or, foreign policies may bring about structural and technological changes. As technological development is a dynamic process with many feedback loops, there are also interdependencies and feedback effects between technological advances, structures and policies.

This complex relationship between policies, markets, industries and technologies is depicted in Figure 1. It illustrates the interdependency not only between German policies and technologies, but also the impact of foreign markets and industry structures. And, national supportive public policies can also affect foreign structures, for example by turning domestic industries into strong, export-oriented industries as stated by Lund (2009).

Figure 1: Interdependencies between policies, market, industry and technology for PV



Approaches from industrial organization, environmental economics and innovation economics such as a technological innovation system (TIS) are employed to analyze this complex system. Discussions in innovation economics and industrial organization on theoretical and empirical findings regarding firm size, market structures and innovation activities go back to Schumpeter 1942, Levin et al. 1985 and others. Recently, the influence of policies on the functions of the TIS, which are described in Hekkert and Negro (2009), del Rio and Bleda (2012) gained attention.

The operationalization and, hence, the analysis of the relationships depicted in Figure 1 is challenging for several reasons: (i) complexity of the relationships, i.e. industry structures or technological changes depend on a variety of factors, (ii) simultaneity and interdependence of relations, for example between policies and structures, and, (iii) limited quality and quantity of data and variables and, hence, limitations in the multivariate analysis. Therefore, this paper starts with a literature review to gain insight into the approaches and results of studies dealing with similar questions.

Accordingly, the paper is structured in two main parts: First, a methodological part that relies on a review of literature followed by an elaboration of the research framework. The literature review focuses on studies analyzing the relations of policies, industry structures and innovation activities. Based on this review and the identified research gaps, we then construct our research framework, specify the research questions, and the approach and data needed. The second part, the empirical part, presents and discusses the quantitative results and derives conclusions for policy makers.

2 Literature review

Given the complex research outline, the literature review is divided into three strands of research that focus on (i) how policies affect the innovation systems and technological change (left part in Figure 2), (ii) how industry structures[1] and firm size influence innovations and hence competitiveness (middle part in Figure 2) and (iii) how policies determine market development and, thus, structures (right part in Figure 2).

Policies and the innovation system approach

There are several research strands concentrating on the topic of innovation and policy impact. However, these differ in their perspective, analysis focus, direction of impacts and approach. While, in environmental economics, core research focuses on the evaluation of policies, market failures, the internalization of externalities, rationality and the optimization of instruments or inputs, innovation economics strives to explain the complexity of factors affecting innovation (Rennings 2000). Environmental economics includes not only research on the environmental impact of policies, but also the impact on innovation activities and structures, and blurs the borders between these research areas. For example, in energy economics, (Nakada 2005) explored the impact of energy market policies on R&D and (Walz, R. et al. 2011,) obtained evidence of a positive impact of demand and R&D policies on patent activities in the wind power sector. (Babiker 2005) integrated aspects from industrial organization into his modelling approach and showed how the effect of climate change policies depends on market structures.

Technological and organizational innovations are seen as the most powerful tool to develop competitive industries and maintain industrial competitiveness (Brown 1994). So, the focus of innovation research has long been on how to foster innovation by establishing structures, institutions and links through policies. A large area of research is that of exploring innovation systems, which include actors, networks and institutions (Kuhlmann, S. und Arnold, E. 2001). This

1 Industry structure refers here to the structure of the supplier market: the number and production volume (in MW) of manufacturers.

structural approach has been expanded by the functional approach of Bergek et al. (2008) and Hekkert et al. (2007), who look at the functions of technological innovation systems (TIS). In the field of renewable energies, for example, Jacobsson (2008) explores how different policies shape the structure and dynamic (functions) of the biopower innovation system. Other authors (Lai et al. 2012) investigate the structure and functional capacities of TIS for carbon capture. Rio and Bleda (2012) combine TIS functions with the impact analysis of renewable energy instruments (REI) from environmental economics. They allocate the potential effects of REI to the functions of TIS and list indicators measuring the impact of REI on the functions of TIS. As indicators of entrepreneurial experimentation and market formation, they suggest the number and types of new market entrants (industry) as well as the number of niche markets created for immature technologies and capacity increases. Their findings show that certain REI are superior to others with respect to their impact on market formation, but that other instruments are needed to activate the other functions, especially concerning knowledge development and diffusion, entrepreneurial experimentation and the mobilization of resources. Although this study provided some first insights into how strongly REI support deployment by learning and/or technology development, there is still a gap in understanding the exact decision mechanism of firms. It is still unclear which factors exactly drive firms to expand their production or explore technologies. Similarly, Hoppmann et al. (2013) investigate the impact of deployment policies and state that it is still unclear "… how exactly deployment policies affect exploration and exploitation ... ." The authors conducted comparative case studies and in-depth interviews. The outcome suggests that, on the one hand, deployment policies induce investments in technological exploration of less mature technologies, but, on the other hand, they are also an incentive to expand the production of more mature technologies. Besides technology maturity, other factors, i.e. industry- or firm-specific factors might influence this decision as well. So, research is still needed on how the combined impact of deployment policy and firm-specific factors affect investments in exploration or exploitation.

Industry structure, firm size and innovations

According to neoclassical economics, firms strive to maximize their profit by investing their limited available resources in the most profitable activity. Therefore, balancing investments in exploitation entailing learning effects with investments in the exploration of technologies requiring research activities is an investment decision based on the expected profitability or enhanced competitiveness. Even though many definitions of competitiveness exist, it is generally understood as the capability of a firm to successfully sell products and ensure a profit. And competitiveness does not only depend on demand and factor conditions, but also on external and firm-specific factors such as firm strategy or structures (Porter 1990). Thus, firm characteristics represent potentially relevant drivers of investment decisions. Although Porter's Diamond Model has been criticized by others, for example (Dunning 1992, 1992), because he neglected the influence of multinational relations and foreign structures (diamond models), his approach still provides a good basis to show the potential impact of policies on competitiveness. According to his model, policies indirectly affect competitiveness via demand factors, related and supporting industries, factor conditions (infrastructure as well as human capital), and firm rivalry and structure. Thus, the decision whether to explore or exploit if demand for PV modules is rising is also driven by rivalry, strategies and structures. Besides these aspects, relative supply of input factors or aggregated factor endowment also explain industry structures (Reeve 2006). Nevertheless, refined strategic management and evolutionary approaches are needed to better understand firms' decisions as (Brown 1994,) states. He developed a model to test the impact of technological innovation on profitability and market structure. His work reveals that "a finer-grained analysis is needed to understand the changing dynamics of competition following technological innovation." Weerawardena et al (2006) assume that, in a competitive industry, firms search for innovative ways of value creation. To measure competitiveness, the authors used market entries, substitutes of products, buyer and supplier power. The results suggest that knowledge development and use of market information positively affect organizational innovations, which in turn affects industry structures via improved performance and competitiveness.

While Porter and others focus on the significance and impact of factor conditions, local and regional linkages and value chain approaches on competitiveness and the resulting industry structures, Schumpeter (1975)[2] pursued a different direction of effects. He discussed structural factors affecting the creation of knowledge and innovation. In the so called "Schumpeter hypotheses" (Kamien and Schwartz 1982), he stated that firm size and market structure matter with respect to innovative activities. Both of his hypotheses have been intensively discussed by authors such as Arrow (1962), Demsetz (1969) and others,

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2 Although he contributed considerably to the emergence of a new research field, innovation economics, he is linked here to the theories of economic development, business cycle and entrepreneurship.

who explored the impact of market structure on R&D spending on a theoretical basis. Further discussions on the relationship of market structure and innovations followed, e.g. by Raider (1998), who lists two proxies for market structures: firm size and market concentration. Although no empirical evidence has been given so far for a clear link between market or industry structures and innovations, the idea is "intuitively appealing" (Raider 1998). Therefore, he looks at the link between market structure and innovation by applying a network model (connections through other actors without direct links) of market competition instead of concentration ratios. His results show stronger innovative activities in markets with high competition than in markets with less competitive pressure. In contrast to Raider (1998), Schumpeter (1942), Arrow (1962) and others, Teece (1996) developed a framework of determinants of innovation that included factor conditions and firm structures and strategy, but also historical development, internal values and cultures, informal/formal organizational structure etc. According to Teece (1996), market structure is not the only determinant of the rate and direction of company-level innovation. Allred and Swan (2005) combine domestic factors (based on Porter 1990) and industrial structures and develop a model of industry structure and national context[3] to test the influence of industry structures and national context on firms' innovative activities. The results provide evidence that industry structures as well as the national context do indeed affect firms' investments in innovations. As a measure of industry structure, they use a concentration measure. Marsili and Verspagen (2002) explore the link between innovation and industrial structures and dynamics in the Netherlands. To depict industrial structures, they use moments of firm size distribution, the average level and standard deviation of labour productivity, concentration indices, changes in productivity levels, market entries and exits as well as the survival rates of firms. Their results suggest that there is a link between market concentration and science-based firms. Similar studies have been conducted by Wu (2012), who found robust support for the contingent effect of market competition and technological collaboration on innovation. To depict market competition, Wu relies on a concentration index, but also uses other company characteristics such as size and age for the analysis. Reichenbach and Requate (2012) study the impact of learning-by-doing and spillovers under different market structures. They map market structures by the number of oligopolistic firms in an industry. Their modelling results show which policies have the least welfare loss under specific conditions. Schulenburg and Wagner

3 National context includes level of development, economic size, and patent protection.

(1991) explore the relation of innovation and market structures. They used the number of recent product introductions into the market or innovations to depict technical changes and a concentration measure - advertisement expenditures, human capital, firm size, private R&D spending - to capture industry structure.

Regarding the link between firm size and innovation, early discussions centre on the problem of the increasing costs of innovations and the limited capacity of small firms to fund these expenditures (Kamien and Schwartz (1982)). The empirical findings of Keßler (1991), who analysed the impact of firm size on growth, provide no evidence that larger firms are the main drivers of innovation and growth. In contrast, the quantitative results of Laforet (2008) support the hypothesis that firm size, strategy and market orientation are linked with innovation. She depicts firm size by number of employees and uses data on start-up, sector affiliation and stability of the operating environment. A more differentiated approach is pursued by (Acs, Zoltan J. and Audretsch, David B. 1987). They find that, in concentrated industries with high capital intensity, larger firms tend to have a relative innovative advantage, while the innovative advantage for small firms is likely to occur in early life cycle stages. Their findings suggest that circumstances play a large role in whether small or large firms are superior innovators. The outcome of (Cohen, W. and Klepper, S. 1996) suggests that large firms tend to spend more on R&D, while their output measured in patents or innovations per input decreases with increasing firm size. (Hashi und Stojčić 2013) derive similar results. They used firm data from the Community Innovation Survey (CIS4) to assess the drivers of the innovation process in two different sets of countries. Besides their main result of a positive relationship between innovation and productivity, they find that large firms “invest more in innovation but innovation output decreases with firm size.” But (Hashi und Stojčić 2013) state that many studies report positive or negative or even neutral impacts of firm’s size on innovation input or output. They explain these divergent findings by citing the influence of specific characteristics of the respective industries or firms in these studies. An analysis of (Costa-Campi et al. 2014) on R&D intensity (R&D per sales) in the energy sector supports the thesis that small firms have an advantage in R&D intensity. However, they also discovered that a specific characteristic influences the result, i.e. younger firms are more likely to perform R&D and spend resources on R&D activities.

The link between firm size or market (industry) structure and a firm’s decision concerning innovative activities has been explored by many researchers. Because they came from an industrial organization background, their research was directed at factors explaining firm sizes, market structures, and innovations, while other factors such as policies, systems or functions of systems, e.g. of TIS, have been neglected. Furthermore, the studies can be distinguished by the direction of impact. While most of the earlier papers look at the impacts of market structures on innovation or production, others concentrate on factors (including industry structures) affecting the competitiveness of firms. There are hardly any papers in energy economics that deal with the impact of technology advances on structures and only a few have investigated the influence of general policies on market structures. One of these papers, a study by Gallet (1997) on public policy and market power, assesses the influence of two policy instruments on market power based on the gap between market prices and the marginal costs of production. The author concludes that some policies could have a strong impact on market power. Later research on energy policies has taken up this issue and is concerned with explaining the impacts of energy policy on industry structures.

Energy policies and industry structures

Recently, researchers have started exploring the impact of energy policies and environmental policies on structures. For example, specific PV-related studies have been conducted by Dewald (2011) and Grau et al. (2012). But although they focus on the PV industry, they remain on a rather descriptive level, listing the firms, production, or production capacities. In another study, Grau et al. (2012) shed some light on the relation between policies and changes in the PV industry in Germany and China. They capture technological development using annual PV production and installation in MW, technical features such as cell technology shares, cell efficiency, material, etc., and the cost and price development of the system and module. They describe the industry’s structure using the firms’ production capacities for silicon, wafer, cells and modules as well as PV equipment. Their analysis remains a descriptive one and indicates the need for a strong tie between deployment policies, technology-push and manufacturer-focused policies. Batlle et al. 2012 qualitatively investigate how the support mechanisms influence the overall energy market structure. To describe the market structure, they refer to market entry barriers, vertical integration and market shares or size of market players. Lund (2009) pursues a similar question when looking at the impacts of energy policy on industry growth in RE, but he applies different research tools such as value chain and commercialization analysis and empirical case studies. He concludes that strong but small home markets and support policies probably lead to increasing industry activities measured in world market or export shares. When looking at the wind market and wind industry, Lewis and Wiser (2007) use quantitative data on installed wind capacities and market shares based on sales of wind turbine manufacturers to explore how local and national policies affect the industry's structure and competition. Their findings emphasize the importance of a local or domestic market boosted by policies for a strong industry. These results are in line with Porter's (1990) Diamond model approach, as the authors' research intention is to shed light on the potential influence of different policies on markets, competition, and structure.

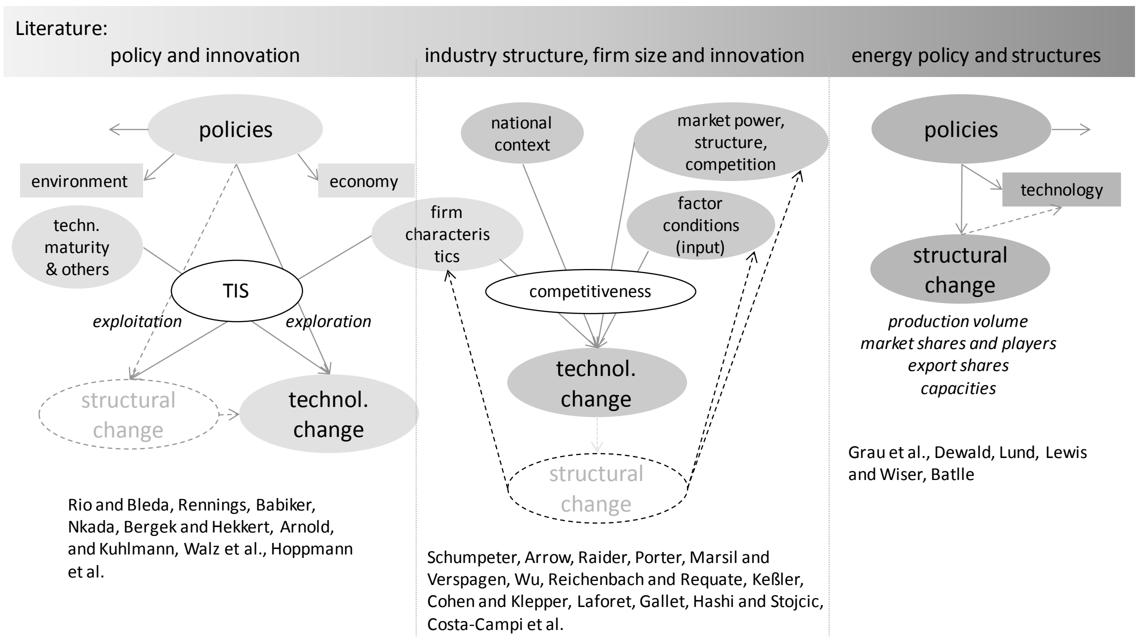
Research gap and derivation of research focus

As outlined above, one strand of research centres on innovation systems and their functions (innovation economics), while environmental economics focuses on the analysis and impact of policy instruments on environmental issues or problems. In contrast, research in other economic fields such as industrial organization, business cycles, etc. looks more at the structures and factors affecting market competition and firms' competitiveness. In this line of research, competitiveness is seen as the result of several factors, such as demand, factor and supply conditions, but also firm-specific aspects such as strategy, management and available resources. Recent studies combine the research approaches of environmental economics and industrial organization by analysing the impact of energy policies on structures, but using structural data as well as policies. Another new aspect of current research is the differentiation of the impact into exploration and exploitation.

In our study, we emulate the innovation functions approach depicted in Bergek et al. (2008) and Hekkert et al. (2007) and analyse the impact of policies on market formation and knowledge generation. In line with Hoppmann (2013), we argue that policies affecting market formation can either induce exploration of technologies, or exploitation of existing know-how. Further, we argue that not only policies impact the innovation system, market formation and knowledge generation, but other factors such as industry structure and firm size that in turn can be affected by policies. Hence, the decision of firms whether to explore or exploit also depends on firm-specific characteristics such as size, strategy and industry structure. As Figure 2 illustrates, this paper intends to complement recent research on policy impacts and structures and innovation by linking the explaining variables such as industry structures and policies to explain technological and structural changes and by adding further explaining variables such as firm characteristics. Technological change, as an endogenous variable, also occurs due to exploration – increase in knowledge (patents) – and structural change occurs due to exploitation – change of firm or industry size – both functions of the TIS. Exploitation is understood as using the existing technical and organizational know-how by taking advantage of learning effects and economies of scale; exploration refers to investigating further technological development and improvements at firm level.

Figure 2 illustrates the different research foci and directions outlined in the literature review above: The links between policies and technological changes, between firms, demand, factor conditions and technological changes, and between policies and structural changes have been explored, but not the impact of policies on structures and the joint impact of policies and structures on technological changes (indicated by the dashed arrows). In addition, recent research has mainly looked at the impact of a (single) policy and not at the joint impact of several policies.

Figure 2: Overview of research streams analysing the impacts of policies, technology and structures

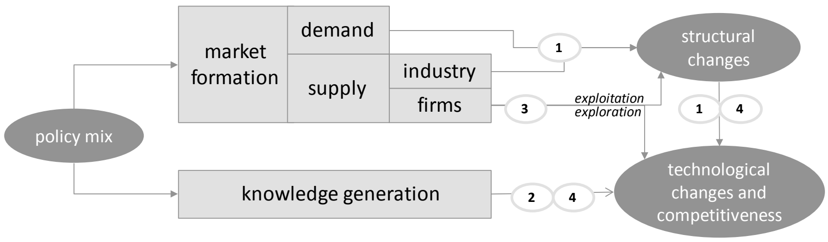


Source: own depiction

3 Methodological approach

This study fills the existing research gap by analyzing the extent to which individual policies as well as the policy mix (combined impact of the policies) influence market formation and the extent to which the resulting market structures and policies together influence knowledge generation. For the analysis, policies are distinguished into demand-focused policies (instruments and strategy), technology-push and supplier-focused policies. The market formation is captured by structural changes e.g. market size for demand (PV power sector) and supply (PV manufacturers). Figure 3 illustrates the resulting research questions (illustrated by the numbers in Figure 3). The analysis is conducted based on the following three hypotheses:

Figure 3: Research gap and questions

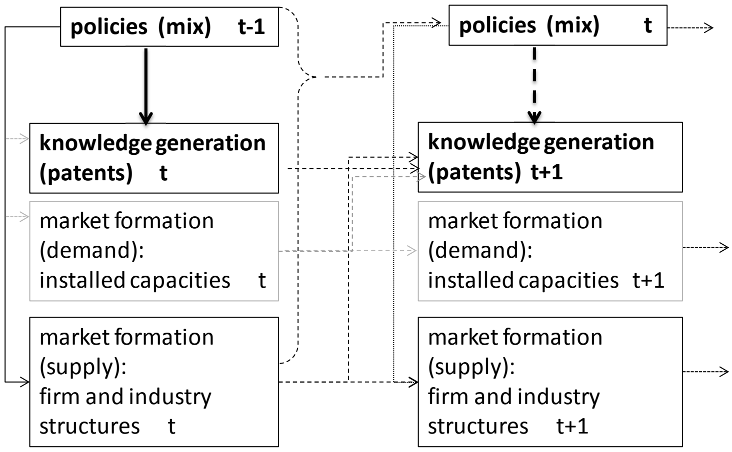


1. Supplier- and demand-focused policies[4] and their mix contribute to **market formation** in the supplier market (PV firm and industry) and demand market (installed PV capacities), i.e. affect the size and heterogeneity of the PV industry as well as the diffusion of technologies. In turn, the structure of the supply industry affects **knowledge generation**. See Figure 4: policies in t-1 affect structures in t and structures in t affect technologies in t+1; (t stands for time unit).
2. Technology-push and demand policies[5] and supplier-focused policies and the **mix of policies** – also contribute directly to increasing **knowledge generation.** See Figure 4: policies in t affect technologies in t+1.

4 Comprise financial instruments supporting demand for RE technologies and policy strategies and objectives; in some studies, demand instruments are also called deployment policies.

5 ditto

Figure 4: Model



3. **Firm characteristics** such as size influence firms' decisions to generate knowledge – exploration – or to develop markets – exploitation. See Figure 4: characteristics in t affect technologies in t+1.
4. **Knowledge generation** is affected by **market formation, policies** and **the mix of policies**. The impact of market formation in t captures the impact of policies in t-1 indirectly, since it is assumed that policies in t-1 affect structures in t. See Figure 4: policies and structures in t affect knowledge generation in t+1.

The analysis is restricted to PV module and cell manufacturers in Germany, to German PV-related policies and patents in PV-related technology fields. The data from Germany covers a period of between 22 to 34 years. First, we employ descriptive and simple bi-variate analytical tools to recognize simple relations between the policy variables and structural variables and technological changes. Second, if data quality and availability permit, significant variables are selected and an econometric analysis is conducted. This is done to avoid low explanatory power due to surplus exogenous variables. To reduce endogeneity problems (policies in t-1 affect structures in t) and account for the indirect impact of policies in t-1 on technological changes (t+1), policies (t) and structures (t) are modelled with the same time lag to technological change (t+1).

It is not trivial to define and select variables reflecting policies, industry characteristics, knowledge generation and technology diffusion. Table 1 gives an overview of the variables used in the analysis. In the following section, the selection of variables is explained and the variables are defined.

3.1 Operationalized policy variables

Four policy variables are employed to analyze how policies affect technologies or industry structures. While policy variables 1a)-c) display a mix of demand instruments, variable 2 is part of a policy strategy promoting the demand for RE. The third variable represents R&D support instruments, which focus on knowledge generation and are also called complementary policies in the literature. The manufacturing support instrument (variable 4) focuses on the manufacturing or supplying industries. The variables are briefly described in the following (see also Table 1). A more detailed description can be found in Breitschopf (2015a):

1. **Demand-pul**l (deployment) **instruments**:
    a) **Margin** (in EuroCent_{2010} / kWh): this incorporates the effects of all demand-supporting policies (in force at that time) and therefore represents a mix of demand instruments. But it also indicates the market situation due to the incorporation of technology costs.
    b) **Incentive** (in EuroCent_{2010} / kWh): this variable indicates the pure pull effect of the demand policy.
    c) **Return** (margin/ LCOE[6]): it takes the value zero if the coefficient is negative, because it is assumed that capacity additions only occur if there is a positive return.
2. **Target** is a demand policy (not an instrument) because it represents a strategy that is focused on increasing RE deployment and therefore increasing demand.
3. **Technology-push policy** (Euro_{2010}volume of public R&D spending on PV) and
4. **Supplier-focused policy** (Euro_{2010}volume of investment support for suppliers).

To account for the joint effect of policies, **policy mix variables (mix)** are applied that multiplicatively combine different policies variables. The idea behind is, that, for example, targets and technology-push policies become more effective if they are aligned and simultaneously applied. For this reason they are linked multiplicatively. Thus, both variables have a strong pull&push effect if they are larger than one while smaller than one their effect is reduced. If one variable is zero they will have no pull-push-effect at all.

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6 Levelized cost of electricity.

3.2 Market formation

The PV industry is a large cross-cutting industry on the supply side of the market. Each life cycle phase of a PV plant has its own value chain. For example in manufacturing, the value chain of a PV module (polycrystalline) ranges from Si-production, wafer, cell and module manufacturing, including steel and glass production as well as machinery suppliers, while operations mainly build on IT software and hardware. In this study, the focus is on PV cell and module manufacturing companies in Germany. The reasons for this focus are that their production activities are clearly attributable to PV and data are available. Furthermore, PV modules account for about one third of the PV investment costs. To describe markets, structural data are needed on the PV industry such as the number of firms, production, market shares, etc. An overview in Annex Table 1 illustrates the variety of indicators applied in research to capture industry structures. For this analysis, the variables used to represent changes in the industry are the production of PV module and cell manufacturers measured in megawatt (MW) and the number of manufacturers.

However, there are no comprehensive statistical data available on the production, products, employment or sales of PV module and cell manufacturers. Diverse sources were used to obtain information on cell and module manufacturing firms, including the journal Photon, IEA-PVPS statistics, Germany Trade & Invest, firm statistics, press news and the internet pages of companies as well as different publications (e.g. Khammas (2013), Dewald (2011)). Even though different types of modules have evolved over time – mono or poly-crystalline, thin-film, etc -, no differentiation was made here due to data limitations.

The industry structure is described using four **industry variables** based on the number and production of PV module and cell manufacturers (see Table 1): (i) the standard deviation of firm size reflects the heterogeneity of the industry, (ii) the concentration ratio captures the degree of market power, (iii) the mean shows the average firm production (size) and (iv) total production indicates the size of the industry.

Three **firm-specific variables** are included to account for the potential influence of firm-specific factors (see Table 1): (i) firm size measured by production in megawatts per year, (ii) experience in PV manufacturing measured by the year in which the company is first reported to have started manufacturing PV cells or modules and (iii) integration of the firm (single firm or part of a corporation).

The demand-side of the market is represented by the annual installed generation capacities of PV plants. In diverse studies, this variable serves either as an indicator of RE policy or as a measure of diffusion. In this analysis, the installed capacities are used to show the size of the PV-based power generation market of the energy sector.

3.3 Knowledge generation

Overall, to measure innovation, proxies are applied for knowledge output (invention) e.g. patent applications (Peters et al. (2012), Walz, R. et al. (2011), OECD (2010)), new products (Harrison et al. (2014), Hashi und Stojčić (2013), Schulenburg and Wagner (1991)) or use of products (diffusion) (Jacobsson and Lauber (2006)), while R&D spending is commonly used as an input indicator (Cohen, W. and Klepper, S. (1996), Hashi und Stojčić (2013), Costa-Campi et al. (2014)).

To measure technological change, this study relies on patent applications as a proxy to capture market-related innovative activities or technological changes even though patent application counts ignore technological changes that are kept secret[7], and disregard the individual "value" of patents or their significance for further research. Three patent analysis strategies are applied (see Table 1):

(i) Patent applications of PV module or cell manufacturers in Germany (patent firm),
(ii) patent applications of all German applicants active in PV-technology research (patent families) and
(iii) patent applications in Germany of all actors working on PV technology development (patent Germany).

The patent application data are taken from Patstat (02/2015 for all PV applicants, and 04/2014 for manufacturers) and include applications up to 2011/12 (detailed information in Annex Box 1).

In addition to these commonly used indicators, the relative patent share (RPS) is applied to show the level of specialization in PV technology. It is closely related to the more commonly used RPA indicator (relative patent advantage by Grupp 1997) and reveals how strongly the share of patenting in the PV "tech-

7 Less than 30% of innovators use patents, while almost 50% and 40% rely on time lead and secrecy, respectively (Rammer 2003).

nology" field in Germany differs from global PV patenting activities. As technological change is commonly applied as an indicator of technological competitiveness (EFI 2014, Breitschopf et al. 2005), it is assumed that stronger specialization will be associated with stronger technological competitiveness in this field.

The specialization indicator is calculated for "patent families" and "patent Germany" (see Annex Box 1):

Formula 1: $RPS_{jk} = \{(P_{jk} / \sum_j P_{jk}) \; / \; (\sum_k P_{jk} / \sum_{jk} P_{jk})\}$

P: number of patent applications; k: country; j: technology field

- RPS family: This is a measure of the worldwide activities of German PV applicants compared to other fields and players and indicates the degree of technological competitiveness. The higher the value, the more German applicants use their knowledge (in PV) compared to other global players.
- RPS Germany: This indicator shows the share of PV patent applications to all applications in Germany compared to the global ratio and highlights the market expectations in Germany, namely the expected market attractiveness. A value above one indicates more PV applications in Germany than in other fields compared to the global ratio.

Technology costs and generation costs can both be used as indicators to show technological advances, and both encompass learning effects and economies of scale. Their magnitude is impacted by other factors as well, for example by the current market situation and prices. Technology costs are incorporated in this analysis via the policy variable margin or return. Finally, installed capacities – annual or cumulative – are often employed to show the diffusion of technologies and market formation. In this paper, installed PV capacities are employed to show market formation on the demand side. The variables applied in the analysis are depicted in Table 1.

Table 1: Policy, PV industry and technology variables

Var	Basic data	Indicators	Indicators show
Policy*	Technology-push	• Public R&D spending: measure of support for technology development	Technology push
	Supplier-focused	• Investment support: measure of support for industry investments (growth)	Manufacturing support
	Demand-pull	• Target: potential investment volume	Policy strategy
		• Margin: profit per generation unit with (without) demand-promoting instruments • Return: margin related to LCOE • Incentive: margin with support vs. margin w/o support	Mix of demand-pull instruments
		• Mix: multiplicative combination of policies	Policy mix (interaction)
Industry - supply	PV cell and module production in MW of firms	• Production of industry: size of industry • Standard deviation of firm sizes • Concentration ratio: market power • Firm production: size of the firm • Number of firms	Market formation (supply) ➔ heterogeneity ➔ competition, ➔ size (exploitation)
	Year of foundation	• Experience: year of foundation (PV business) minus year of observation	
	Affiliation	• Integration: vertical or horizontal	
Technology	PV patent application	• PV patent applications of: ○ PV module or cell manufacturers Ger. ○ German applicants worldwide ○ Applications in Germany • Specialization: ○ RPS family ○ RPS Germany	Knowledge generation (technology) ➔ exploration (new technologies) ➔ competitiveness ➔ market expectations and attractiveness
Power	Installed PV capacity	• Growth of installed PV capacity in Germany	Market formation (demand) - diffusion into energy sector

3.4 Approach and models

To assess and display the impact of policies on market formation and knowledge generation descriptive, bi- and multi-variate analyses[8] are conducted as depicted in Figure 4. A time lag of one year is applied to account for an

8 Including tests for e.g. heteroskedasticity, multicollinearity, omitted variable bias, autocorrelation, normal distribution.

adjustment period (rigidity) and potential endogeneity problems. Policies and market formation and knowledge generation are set into an additive relationship as a multiplicative linkage would delete all effects as soon as the value of one variable is zero. However, to address at least partially a joint effect of policies, policy mix variables as a multiplicative linkage of selected policies is included. The impact of policies on market formation is shown descriptively for the demand and supply market and is backed by correlation analyses. To show the impact of market formation on technological competitiveness (knowledge generation) a multi-variate analysis is conducted based on Formula 2:

Formula 2 :

$$\textit{RPS fam}_{t+1} = \textit{market formation variables}_t + \textit{external variable}_t + \textit{error}_t$$

Market formation: annual installed capacity or standard deviation (heterogeneity); external variable: growth of German GDP(real); t: time unit year

Correlation and multiple regression analyses shed light on how policies affect knowledge generation. The model is depicted in Formula 3:

Formula 3:

$$\textit{RPS fam}_{t+1} = \sum_i \textit{policies}_{i\,t} + \textit{external variable}_t + \textit{error}_t$$

Policies $_i$: demand instrument mix (margin, incentive, return), supplier focused and technology push-policy, policy mix variables (mix1 = target x return; mix2= target x margin, mix3= target x R&D support);
external variable: intensity of competition= annually installed capacity (MW) – annual production (MW); t: time unit year

To take a closer look on the link between firm characteristics and technological changes, a fixed and random effect regression analysis is employed (see Formula 4). They allow for testing impacts of variables over time within entity but also between entities (here: firms). As under increasing demand for RET firms either explore or exploit (Hoppmann 2012), the question arises, whether large or small firms tend to invent or innovate more (Schumpeter Hypothesis). The size aspect is captured by the variable firm size (MW production) and integration level. Moreover, experience as further explaining variable is included. It is assumed that firm size as well as experience and integration in t affect the firm's decision to explore further technology (measured in patent applications) in t+1:

Formula 4:

$$\textit{Patent application firms}_{t+1} = \sum_i \textit{firm characteristics}_{i\,t} + \textit{error}_t$$

Firm characteristics $_i$: experience, integration, size; t: time unit year;

Finally, to capture the impact of market formation and policies on technological competitiveness a multiple regression analysis is conducted based on Formula

5. It assumes that policies in t affect directly technological competitiveness (RPS) in t+1 and indirectly through market formation in t+1. Therefore, market formation in t is included as explanatory variable for RPS in t+1.

Formula 5

$$RPS\ fam_{t+1} = \sum_i policies_{i\,t} + market\ formation\ variable_t + error_t$$

Market formation: annual installed capacity or standard deviation (heterogeneity); Policies i: demand instrument mix (margin, incentive, return), supplier focused and technology push-policy, policy mix variables (mix1 = target x return; mix2= target x margin, mix3= target x R&D support);

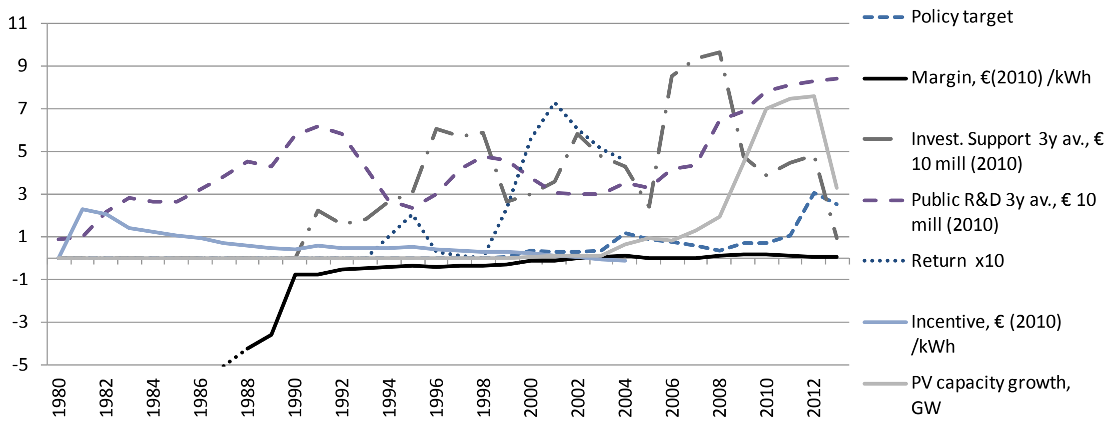
4 Results

4.1 Impact of policies on market formation and market formation on knowledge generation

4.1.1 Impact of policies on market formation

When looking at PV market formation, the market is split into the demand side – the power generators – and the supply side – project developers, system providers, and the manufacturers of PV modules, cells or inverters. The **demand side** is depicted by the annual capacity growth of PV plants. The capacity growth and the evolvement of policies over time are illustrated in Figure 5. While R&D policies supporting PV have been applied over a long period with a varying volume of public support but a constantly rising tendency, supplier- and demand-focused policies only emerged around the beginning of the 90s. The policies target different actors – manufacturers (suppliers) and PV power generators (demanders). During the period examined, the policy variables margin and return were sometimes negative or zero, respectively, but showed highly positive values between 2008 and 2012, with a peak in 2009/10. Return and margins declined after 2010 due to adjustments in demand policies (FIT adjustments). Although there is a widely held belief that demand instruments have strongly impacted capacity growth and hence market formation, it is difficult to prove these relations quantitatively, because there is no simple correlation between policies and capacity growth. This study applies a multiplicative combination of policies to account for this challenging issue. Mix1 combines targets and return, mix2 targets and margin, mix3 targets and R&D.

Figure 5: Policies and PV energy market formation over time



Source: own calculations based on diverse sources (Bafa, Förderkatalog der Bundesregierung, BMWi)

Correlations between policies and market formation with a lag of one year underpin the findings (Table 2). Market formation in terms of power generation measured by capacity growth correlates highly with returns, while the relation between targets, margins (incentive) and capacity growth is not significant (1990-2013). This is a plausible result, because the margins evolved continuously from negative to slightly positive, while capacity growth was close to zero between 1980 and 1990 (in absolute terms). There are also significant correlations for the policy mix. The link between capacity growth and R&D support is significant and positive in both periods, even if there is no direct theoretical link between these two variables.

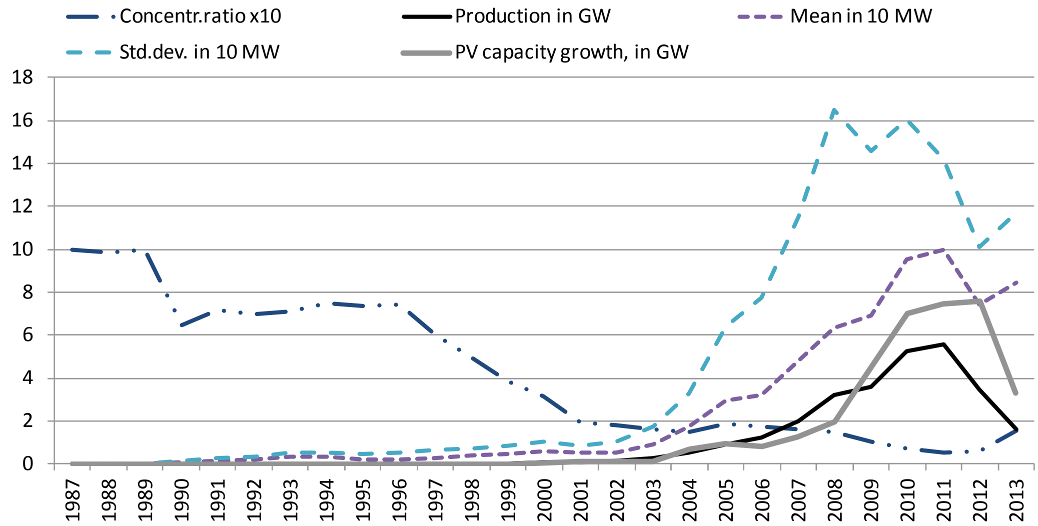
Table 2: Correlation between policies in t and installed PV capacity in t+1 - demand market

	Capacity in t + 1 (capacity in t)							
in t	Target	Margin	Return	Inv.Sup.	R&D Sup.	Mix1	Mix2	Mix3
1980 – 2013	**0.52***		**0.94**		**0.73**	**0.62**	**0.72**	**0.54**
1990 – 2013		**0.63**	**0.94**		**0.75**	**0.59**	**0.71**	

Source: own calculation; Note: significance level at 0.05; *correlation coefficient of 0.73 between policies in t and capacity in t

Market formation from the supplier perspective (**supply market**), i.e. the development of the PV supplier industry in Germany, is depicted in Figure 6 by the size of the industry, the average firm size (both in MW), the heterogeneity and competition of the PV industry in Germany.

Figure 6: Heterogeneity, market concentration and size of PV supplier industry in Germany



Source: own composition, based on diverse data sources: GTAI (2004-2013), Photon (1995-2012), Khammas (2013), Dewald (2011), IEA-PVPS (2000-2012).
Note: concentration value of 10 indicates strong concentration (i.e. one firm)

The German PV industry showed a steady increase in the number and size of cell and module manufacturers up to 2011, while its heterogeneity (standard deviation) peaked in 2008 (Figure 6). In contrast, the market power (concentration ratio) of the dominating firms decreased until 2011. The decline in the industry's size occurred in parallel to significant reductions in feed-in tariffs and increasing competition from abroad.

Regarding the correlation results between industry structures and policies (lag of one year), there is a highly significant and strong correlation with demand instruments, here measured by "return" or "margin", from 1990 onwards (Table 3). Before 1990, margins were negative and module production was close to zero. Public investments grants, approved between 1990 and 2013, appear to correlate with industry size and heterogeneity. For example, the values between 1980 and 1990 were close to zero for both variables – industry and policy. In contrast, technology-push policy (R&D support) is correlated positively with standard deviation, average firm and industry size in both periods (1980-2013 and 1990-2013), while the pure demand-pull instrument (incentive) shows no correlation. The policy mixes correlate mainly with heterogeneity and average firm size.

Table 3: Correlation between policies in t and industry structures in t+1

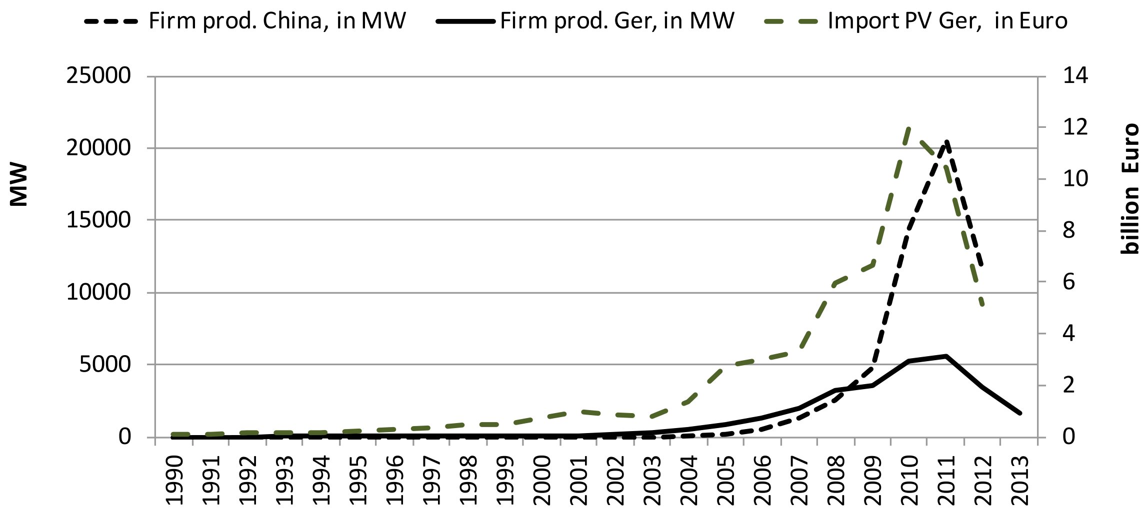
	Stand. deviation firm size in t + 1							
in t	Target	Margin	Return	Inv.Sup.	R&D Sup.	Mix1	Mix2	Mix3
1980 - 2013	**0.71**		**0.78**	**0.66**	**0.67**	**0.64**	**0.69**	**0.67**
1990 - 2013	**0.67**	**0.73**	**0.76**		**0.63**	**0.62**	**0.68**	**0.64**
	Concentration Ratio in t + 1							
in t	Target	Margin	Return	Inv.Sup.	R&D Sup.	Mix1	Mix2	Mix3
1980 - 2013								
1990 - 2013		**-0.87**						
	Production in MW in t + 1							
in t	Target	Margin	Return	Inv.Sup.	R&D Sup.	Mix1	Mix2	Mix3
1980 - 2013			**0.83**	**0.54**	**0.65**		**0.61**	
1990 - 2013		**0.67**	**0.81**		**0.63**		**0.58**	
	Mean firm size in MW in t + 1							
in t	Target	Margin	Return	Inv.Sup.	R&D Sup.	Mix1	Mix2	Mix3
1980 - 2013	**0.74**		**0.89**	**0.57**	**0.73**	**0.73**	**0.78**	**0.72**
1990 - 2013	**0.69**	**0.73**	**0.88**		**0.72**	**0.71**	**0.78**	**0.70**

Source: own calculation; Note: all significant at 0.05

The intuitive assumption that market formation in the PV power generation market and PV supplier market can be attributed to demand-pull, technology-push and mixes of policies is supported by these statistical correlations. These correlations can be explained by the fact that investment and R&D support reduce the financing volume on the supplier side and, hence, increase returns on equity (ROE), which is assumed to be the main incentive for investing in production or knowledge generation. In addition, a strong demand impulse signals a growing market with possibly high market prices, and thus, an increase in producers' surplus. And the policy variable targets in combination with demand-pull or technology-push instrumentes combine longterm perspectives and financial aspects.

However, market formation is also affected by external factors. Looking at Figure 7, it becomes clear that, before 2008, global competition measured by PV module imports (in Euro 2010) and Chinese PV module and cell production was rather weak, and did not represent major pressure or competition for German manufacturers. But with the increasing demand for PV in Germany (increasing PV capacity instalments), Chinese PV manufacturers have experienced even stronger growth than German suppliers. This growth has led to increasing competition and growing PV markets with potential effects on the German market, where demand exceeded supply. This is backed by strong correlations of PV module imports and Chinese PV module and cell production with annually installed capacities in Germany. These are highly significant at 0.97 and 0.86, respectively. And industry structures in Germany (standard deviation and production) correlate with Chinese production (0.68/0.68) and PV imports (0.88/0.93). Moreover, PV imports (0.84) and Chinese PV production (0.96) strongly correlate with return lagged by one year in the period 1990-2013. This backs the hypothesis that domestic demand policies also affect markets and structures abroad. Further econometric analysis cannot be conducted due to data limitations.

Figure 7: PV module and cell production in Germany and China and imports



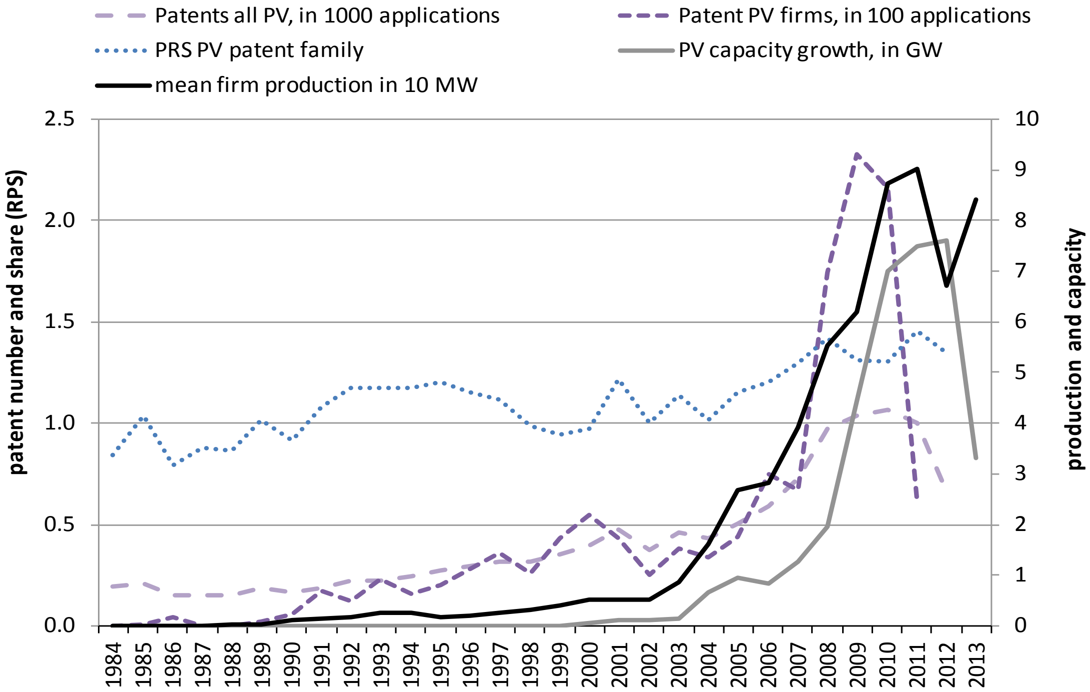
Source: own depiction based on Photon, Eurostat

4.1.2 Impact of market formation on knowledge generation

As already stated, it is assumed that that both types of market formation (supplier and demand side) influence knowledge generation. Figure 8 displays the capacity growth that follows PV patent applications of manufacturers and all PV-related applications with a lag of 1-2 years. Further, average firm size has increased in line with patent applications, but the peak lags by 1-2 years. Apparently, other factors have driven patenting activities. For example, expectations about market formation, reflected by the magnitude and period of validity of targets, could be a potential driver of patent applications in Germany.

Table 4 depicts the correlation coefficients between market formation (industry structure and capacity) lagged by one year with knowledge generation (German patent family applications and firm patent applications Germany) and technological competitiveness (PRS Fam). The magnitude of most of the structural variables is strongly linked to technology advances and market expectations and formation. Not surprisingly, the market attractiveness measured by RPS Germany does not correlate significantly with market formation.

Figure 8: Supplier and demand market formation and technology changes in Germany



Source: patstat, BMWi 2014, own compilation

Table 4: Correlation between market formation and technological changes, 1983-2012

	stand.dev.	production	mean firm size	capacity
PV firm Patents t + 1	**0.87**	**0.73**	**0.76**	**0.56**
PRS Fam t +1	**0.74**	**0.69**	**0.73**	**0.78**
German PV Patent family t + 1	**0.96**	**0.89**	**0.92**	**0.62**

Source: own calculation; Note: significant at 0.05

Regressions (see formula 2) with variables of the industry structure, e.g. heterogeneity, and external factors such as GDP show an R^2 adjusted of 0.61, and significant values at the 0.05 level (see Annex Regression 1). Replacing heterogeneity by installed capacities as the explanatory variable (correcting for serial correlation) displays significant coefficient values as well (R^2 adjusted of 0.62). This implies that technological competitiveness and hence the technological advances of German companies increase with a growing supply and demand market.

4.2 Impact of policies on knowledge generation

In contrast to demand- (target) and supplier-focused policies, R&D policies are assumed to exert direct influence on technological advances. Figure 8 clearly shows that the strong growth in patent applications (manufacturers and all actors) beginning in 2007 follows the first peak in targets with a lag of 3-4 years, while there is no very clear pattern of development between public R&D spending and patent applications. In contrast to patent applications, technological competitiveness, illustrated here by RPS (Fam), grow less strongly over time. Correlations between policies and technology variables (lagged by one year) reveal some interesting results:

- **German patent applications** and **patent applications in Germany** correlate significantly with most of the policy variables except for incentive; but the highest correlation is with the policy mix (multiplicative combination of target and R&D support) (0.87 with German patent families and 0.83 with patent applications in Germany).
- **Patent applications of the German PV module and cell manufacturers** display a correlation of 0.65 with the policy mix and 0.71 with investment support, because firm patents and the policy mix or investment support take off after 1990.
- The **attractiveness of the German market** (RPS Ger) shows only a weak correlation with margins (0.54), but a stronger correlation of 0.62 with incentives.
- The technological **competitiveness** (RPS Fam) of German applicants is correlated with investment support (0.63) and the policy mix (0.7).

Although economic theory and empirical findings indicate that R&D activities induce knowledge generation and entrepreneurial experimentation, and hence promote technological competitiveness, demand instruments seem to have a stronger correlation with technological changes than public R&D support alone. However, the combination of target and R&D support reveals a strong link with technological changes and competitiveness.

Besides policies, other external factors such as competition or manufacturing of PV modules in China or economic growth can impact knowledge generation and technological exploration.[9] To account for these additional factors, PV im-

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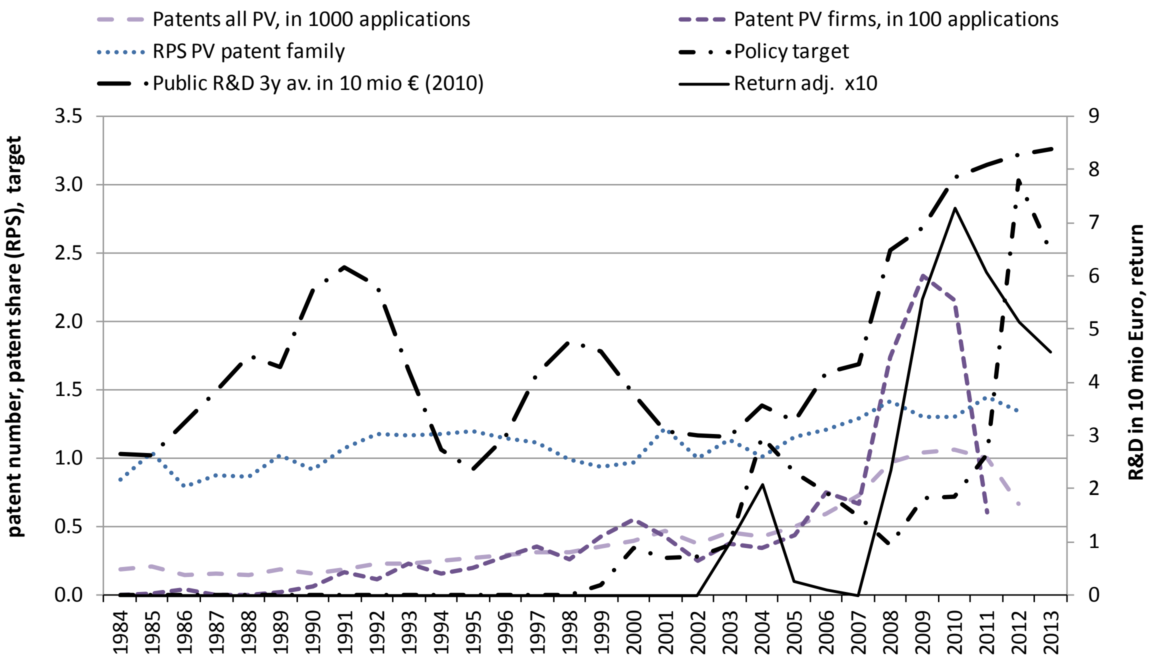
9 But because the production in China only took off about a decade ago, the number of observations is too limited to be used in a multivariate econometric analysis.

ports and GDP are added to the analysis. The correlation coefficient of these factors supports the assumption that general positive growth prospects and imports go hand in hand with increased knowledge generation and technological exploration (see Annex Correlation Results 1). In contrast, growth and imports do not correlate with market attractiveness.

Figure 9: Knowledge generation and PV technology diffusion over time in Germany



Source: own depiction, based on patstat, BMWi 2014

In addition, a multivariate regression analysis (see Formula 3) is conducted with the RPS family variable as the endogenous variable and the policy variables margin, incentive, R&D and investment support as well as policy mix as explanatory variables (mix2: target multiplied by margins and mix 3: target multiplied by R&D support). "Intensity_compet" is included as an external factor. This shows the difference between annually installed capacity and produced modules or cells (in MW) in Germany. Regressing technological competitiveness on these variables displays an R^2 adjusted of about 0.76 (R^2 of 0.69), and significant coefficients for policy mix3 and incentive at 0.05 significance level (Annex Regression Results 2). Reducing the number of explanatory variables to demand-pull instruments (incentive), supplier-focused policies (investment support) and a combination of technology push and strategy (policy mix 3) underpins the results (R^2 = 0.75, R^2 adjusted = 0.72 and significant coefficients at

0.02 level): Policy mix3 explains technological competitiveness to a large degree followed by the pure demand-pull effect (incentives). The significant coefficient of investment support with competitiveness can be explained by the relaxing impact of investment support on firms' budgets, allowing for (more) technological exploration. There were no significant results for a regression with the same variables on market attractiveness.

4.3 Impact of firm characteristics on knowledge generation

To account for the impact of specific firm characteristics on the firm's decisions whether to exploit existing know-how and production technologies and expand production, or explore further technological potential and develop new or improved products, three characteristics are taken into account: the firm size measured by its production of PV modules (MW), the age of the firm as a proxy for its experience and know-how, the integration of the firm into a corporation and its patent applications reflecting the generation of knowledge.

The analysis is based on panel data (patent applications and production in MW) of PV module and cell manufacturers in Germany between 1991 and 2011. Cumulated patent applications are also used to account for the influence of patenting activities in year t-i on patenting activities in year t (see Formula 4). The Hausman test of fixed versus random effects models suggests using the fixed effect model to explain cumulated patenting activities (or patent applications per year). It reports an overall R^2 of 0.29 (0.15), a within-R^2 of 0.34 (0.10) and between-R^2 of 0.25 (0.36), with highly significant coefficients for firm size and significant coefficients for integration, while experience is insignificant (see Annex Regression Results 3).

These findings indicate that firm size and the integration of a firm into a corporation explains patent applications to a small extent, i.e. larger and integrated firms tend to generate slightly more knowledge than smaller and non-integrated firms, while experience appears to have no impact on knowledge generation. Or vice versa, firms with a larger knowledge base (patents) and integration in a corporation tend to have a larger module or cell production than those with a smaller knowledge base.

4.4 Impact of market formation and policies on knowledge generation

As (Hashi und Stojčić 2013) have already stated innovations in firms or in an industry are influenced not by one single factor such as one policy measure, or firm size, or market structure, but by a bundle of varying factors.

To account for this complexity, policy mix variables are considered as explanatory variables. Market formation (installed capacity and heterogeneity) is also included, because especially the latter showed strong significance for technological competitiveness and correlates highly with other industry variables. In this context, industry structures depend on policies as well and policies in turn might depend on technological changes and structures (endogeneity). To avoid this problem, the explanatory variables are lagged by one year. The approach is based on Formula 5. The results are depicted in Annex Regression Results 4. To reduce the number of variables, the most significant policies (margin, incentive and R&D support) are included (see Table 5). The multiple regression results display an R^2 adjusted of 0.79, and significant values for all selected variables at the 0.05 significance level (and no problems with multicollinearity, heteroskedasticity, autocorrelation, distribution of error term, see Annex Regression Results 4). Replacing heterogeneity by capacity as the explanatory variable shows significant results for margin and capacity as well (R^2 adjusted of 0.64; no problems with multicollinearity, heteroskedasticity, autocorrelation, distribution of error term see Annex Regression Results 4).

Table 5: Technological competitiveness (t+1), industry structures (t) and policies (t)

Source	SS	df	MS
Model	.743890056	4	.185972514
Residual	.164200675	25	.006568027
Total	.908090732	29	.031313474

Number of obs	= 30
F(4, 25)	= 28.31
Prob > F	= 0.0000
R-squared	= 0.8192
Adj R-squared	= 0.7902
Root MSE	= .08104

F.RPS_fam	Coef.	Std. Err.	t	P>|t|	Beta
standdevsize	.0043709	.0007353	5.94	0.000	.936624
margini~2010	.0142198	.0061693	2.30	0.030	.263308
publicr~2010	-.0286753	.0153965	-1.86	0.074	-.2608259
Incentive	.1154754	.0365959	3.16	0.004	.3862869
_cons	1.088764	.0567589	19.18	0.000	.

The empirical findings suggest that (i) the structural variable heterogeneity dominates the results and explains the RPS to a large degree and (ii) demand instruments positively affect the technological competitiveness of the PV industry. The findings also reveal that demand instruments have a significant influence, while policy strategies seem insignificant. The same applies to supplier-focused policies. R&D policy is reported to have a negative impact on technological competitiveness, which is puzzling. However, if we assume that technological change is market-driven, policymakers will cut public policy support if the market is growing. Adding joint policy mix variables (multiplicative combination of target, margin, return, R&D) yields insignificant results. Overall, it is not the policy mix, but demand instruments that largely explain technological competitiveness, either directly or indirectly through market formation (supply).

5 Conclusions

This study investigates the relations between the PV market (supply and demand) and policies and technology. Correlation and regression analyses are used to investigate the impact of policies on market formation – PV industry size and structure for the supply side and installed capacity for the demand side – and knowledge generation (patent applications), the link between market formation and knowledge generation, the influence of firm-specific factors as well as the combined impact of market formation and policies on technological changes and competitiveness. The policies applied in this paper comprise demand-pull instruments, deployment targets, technology-push (public R&E spending) and supplier-focused policies (public investment support). To take into account the joint impact of policies, a multiplicative combination of the policy variable target with other policies e.g. R&D support is applied. The analytical findings show:

- Demand-pull policies seem to affect market formation (demand and supply), especially if targets are combined with demand-pull and technology-push instruments. However, external factors such as imports and Chinese PV module production also affect the demand for and supply of PV modules. In return, demand-pull instruments in Germany have impacted Chinese PV module production and imports as well.
- Knowledge generation and the technological competitiveness of German technology providers correlate strongly with market formation, especially with industry structures (supply).
- Knowledge generation and technological competitiveness are also directly affected by policies. Especially the demand-pull instrument (incentive) and the mix of target and technology-push explain the technological competitiveness of German technology providers to a large degree.

- Technological competitiveness is strongly shaped by market formation which in turn is driven by demand-pull instruments.
- Finally, firm-specific characteristics such as the degree of corporate integration and firm size only show a slight influence on the firm's decision to explore further technological changes instead of exploiting existing knowledge and increasing production. Hence, the finding that larger firms generate more knowledge than smaller ones cannot be supported.

Technology-push instruments are crucial for technological changes, as they pave the way for basic research leading to emerging technologies and markets. The combination of ambitious deployment targets and sufficient public R&D support seems to be a very promising technology-push policy mix to address technologies close to market maturity. Long-term deployment targets anchored n the RE act are especially important for technology providers as they signal a long period of validity of policies. Low market, performance and policy risks (Breitschopf and Pudlik 2013) are given as long as policies and market development promise a certain future cash-flow.

Demand- and supplier-focused policies are primarily seen as policies contributing to market formation, but market formation decisively influences knowledge generation as well. So the German Renewable Energies Act has contributed considerably to technological changes: Increasing demand for PV modules leads to rising prices for PV modules. Due to the anticipated returns, the supplier market, the number of actors and production increase as does competition. To strengthen their market position and competitiveness, firms decide to invest in technology development and / or in production expansion. When expanding, they benefit from learning effects and economies of scale; when exploring new technologies, they benefit from innovations. This has been observed in the Chinese market: Chinese module manufacturers benefited from efficiency improvements in production lines and from economies of scale and have become very competitive. Moreover, R&D efforts have been increasing, leading to growing patent applications of Chinese technology providers. This competitiveness put German manufacturers under pressure and together with decreasing feed-in tariffs (decreasing demand) resulted in reduced production or shutdowns. German manufacturers have lost significant market shares but not their technological competitiveness so far. Thus the access to or availability of technology as well as the development potentials (Masini and Menichetti 2012) and expectations about future competitors or market entries etc. are crucial factors that influence investment decisions and thus shape an industry's structure. To account for this latter aspect, foreign PV policies and competitiveness are key factors as well.

Although the results underpin the theoretical assumptions about demand-pull instruments and technological changes, they should be interpreted with caution. The analyses are limited by the availability of data and the modelled relations. For example, positive margins or returns have an impact on capacities once they exceed a certain minimum threshold. The combination of appropriate policies might have a stronger impact on market formation than the sum of each single policy. For instance, the target variable might have zero effects if there is no corresponding incentive, margin or return for investors. And, vice versa, if there is no planning certainty, political reliability or targets, then even a high margin fails to induce market growth. Part of this combined effect has been taken into account by the multiplicative combination of two variables, but these represent first approaches which need further research.

Regarding the goal to promote technological change and the technological competitiveness of the German PV industry, the findings show that a) demand instruments are very important as they induce technological changes via market development and b) the design of policies should take into account global technology and market development and c) a policy mix with a long term perspective signaling planning security should be applied rather than isolated policies.

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Annex

A-Table 1: Variables used in diverse studies to describe industry structures

Indicators used to depict industry structures
Production (MW) or installed MW for generation of PV power
Market exits and entries and barriers
Buyer and seller market power
Production or production capacity suppliers
Firm size (production or sales distribution)
Number of employees
Difference between market price and marginal cost
Network size
Concentration indices
Product differentiation
Vertical or horizontal integration
Survival rate, firm age
(Changes in) productivity
Number of firms
World market share
Export share
Product substitutes
Number of niche markets

Source: own composition, based on literature

Annex Box 1: Patent Information

Patent classes

Patent applications classes (IPC code) for firms:
H01L 25/00' 31/04' 31/052' 9/20' 51/4%' 31/18' 31/00' 33/00'; H02N 6/00'; E04D 1/30'; G02F 1/136'; G05F 1/67'; G01L 25/00'; H02J 7/35'

Patent application classes (IPC code) for all applicants:
H01L 27/142, 31/00-31/078 H01G 9/20 H02N 6/00; H01L 27/30, 51/42-51/48; H01L 25/00, 25/03, 25/16, 25/18, 31/042; C01B 33/02, C23C 14/14, 16/24, C30B 29/06; G05F 1/67; F21L 4/00 F21S 9/03; H02J 7/35; H01G 9/20 H01M 14/00; C12N 1/13-21, 5/10, 15/00

Patent application of PV module or cell manufacturers in Germany

The firm patent application data in Germany comprises firms, which are listed in the PV industry data base and have filed a patent in Germany in PV module or PV cell related patent classes. All patent applications of institutions or universities or non-listed firms (manufacturers in the PV industry data base) as well as applications apart from PV module or cell technology fields are excluded in this patent data set. These patent data is used to answer the questions, how strongly have policies and firm characteristics such as firm size influenced technological changes in the PV industry.

Patent application of all German applicants active in PV-technology research (patent families)

All German actors applying for a PV-related patent worldwide in the specified IPC classes, i.e. the number of patent families with singletons

Patent applications in Germany of all active actors in PV technology development

All applicants in the specified IPC codes that have applied for a patent at the German patent office (DPMA)

Formula 1:

$RPS_{jk} = \{(P_{jk} / \sum_j P_{jk}) \ / \ (\sum_k P_{jk} / \sum_{jk} P_{jk})\}$

P: number of patent applications; k: country; j: technology field

Annex Regression Results 1: Technological competitiveness and market formation and external factors, 1983-2012

```
Linear regression                                      Number of obs =      30
                                                       F(  2,    27) =   34.85
                                                       Prob > F      =  0.0000
                                                       R-squared     =  0.6444
                                                       Root MSE      =  .10935

------------------------------------------------------------------------------
             |               Robust
   F.RPS_fam |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
standdevsize |   .0021626   .0006158     3.51   0.002      .000899    .0034262
         gdp |   .6877557   .2677063     2.57   0.016     .1384676    1.237044
       _cons |   .4043014   .2462683     1.64   0.112    -.1009994    .9096022

      Source |       SS       df       MS              Number of obs =      30
-------------+------------------------------           F(  2,    27) =   24.47
       Model |  .585214701     2  .292607351           Prob > F      =  0.0000
    Residual |  .322876031    27  .011958372           R-squared     =  0.6444
-------------+------------------------------           Adj R-squared =  0.6181
       Total |  .908090732    29  .031313474           Root MSE      =  .10935

------------------------------------------------------------------------------
   F.RPS_fam |      Coef.   Std. Err.      t    P>|t|                     Beta
-------------+----------------------------------------------------------------
standdevsize |   .0021626      .0008     2.70   0.012                 .4634092
         gdp |   .6877557   .2976389     2.31   0.029                 .3961421
       _cons |   .4043014   .2668836     1.51   0.141                        .
```

(Ho: normal distribution of error term exactly at significance 0.05)

Linear regression

Number of obs =	30
F(3, 26) =	21.85
Prob > F =	0.0000
R-squared =	0.6631
Root MSE =	.10847

F.RPS_fam	Coef.	Robust Std. Err.	t	P>|t|	[95% Conf.	Interval]
e						
L1.	.3712744	.1607968	2.31	0.029	.040752	.7017969
PVCapacity~h	.0233481	.0112872	2.07	0.049	.0001469	.0465494
gdp	1.041692	.2455377	4.24	0.000	.5369821	1.546402
_cons	.1002815	.2269621	0.44	0.662	-.3662458	.5668088

Source	SS	df	MS
Model	.602194525	3	.200731508
Residual	.305896207	26	.011765239
Total	.908090732	29	.031313474

Number of obs =	30
F(3, 26) =	17.06
Prob > F =	0.0000
R-squared =	0.6631
Adj R-squared =	0.6243
Root MSE =	.10847

F.RPS_fam	Coef.	Std. Err.	t	P>|t|	Beta
e					
L1.	.3712744	.1845353	2.01	0.055	.2320491
PVCapacity~h	.0233481	.0126397	1.85	0.076	.258431
gdp	1.041692	.2413101	4.32	0.000	.6000068
_cons	.1002815	.2219851	0.45	0.655	.

(Ho: normal distribution of error term at significance level 0.045)

Annex Correlation Results 1: Correlation between technology and other factors

```
. pwcorr   gdp    PV_Imports_2010  Intensity_Compet F.Ger_PV_pat_App F.PV_Pat_in_Ger  F.
> RPS_fam   F.rps_Ger  in 3/34, obs sig star(5) sidak
```

	gdp	PV_~2010	Intens~t	F.Ger_~p	F.PV_P~r	F.RPS_~m	F.rps_~r
gdp	1.0000						
	32						
PV_Impo~2010	0.6989*	1.0000					
	0.0003						
	31	31					
Intensity_~t	0.3206	0.5111	1.0000				
	0.8212	0.0671					
	31	31	31				
F.Ger_PV_p~p	0.8313*	0.8212*	0.1611	1.0000			
	0.0000	0.0000	1.0000				
	30	30	30	30			
F.PV_Pat_i~r	0.8000*	0.8613*	0.2913	0.9725*	1.0000		
	0.0000	0.0000	0.9289	0.0000			
	30	30	30	30	30		
F.RPS_fam	0.7404*	0.7103*	0.2409	0.7938*	0.7756*	1.0000	
	0.0001	0.0002	0.9907	0.0000	0.0000		
	30	30	30	30	30	30	
F.rps_Ger	0.1662	0.1247	0.0781	0.1292	0.1790	0.5446*	1.0000
	1.0000	1.0000	1.0000	1.0000	0.9999	0.0384	
	30	30	30	30	30	30	30

Annex Regression Results 2: Technological competitiveness and market expectations

```
. regress  F.RPS_fam  margininkwh2010  mix3  mix2 publicrd3yavin10mio2010 investsupport3
> yavin10mio2010  Intensity_Compet Incentive if year < 2012 & year >1981
```

Source	SS	df	MS
Model	.695189658	7	.099312808
Residual	.212901074	22	.009677322
Total	.908090732	29	.031313474

Number of obs	=	30
F(7, 22)	=	10.26
Prob > F	=	0.0000
R-squared	=	0.7656
Adj R-squared	=	0.6910
Root MSE	=	.09837

F.RPS_fam	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
margini~2010	.0043241	.0101809	0.42	0.675	-.0167899	.025438
mix3	.0661982	.0219196	3.02	0.006	.0207397	.1116567
mix2	-.7538519	.7976001	-0.95	0.355	-2.407973	.9002695
publicr~2010	.0078291	.0166271	0.47	0.642	-.0266534	.0423116
invests~2010	.0152202	.0121717	1.25	0.224	-.0100223	.0404628
Intensity_~t	-.0000239	.0000584	-0.41	0.686	-.0001451	.0000972
Incentive	.1017668	.0454537	2.24	0.036	.0075016	.196032
_cons	.9025763	.0883278	10.22	0.000	.7193957	1.085757

Note: tests for heteroskedasticity, multicollinearity, normal distribution, autocorrelation, and omitted variables report no problem (significance level α=0.05)

Mix2: policy target margin;   Mix3: policy target * R&D*

```
. regress  F.RPS_fam   mix3    investsupport3yavin10mio2010   Incentive if year < 2012 &
>  year >1981

      Source |       SS       df       MS              Number of obs =      30
-------------+------------------------------           F(  3,    26) =   25.90
       Model |  .680423296     3  .226807765           Prob > F      =  0.0000
    Residual |  .227667436    26   .00875644           R-squared     =  0.7493
-------------+------------------------------           Adj R-squared =  0.7204
       Total |  .908090732    29  .031313474           Root MSE      =  .09358

------------------------------------------------------------------------------
   F.RPS_fam |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
        mix3 |   .0530915   .0094692     5.61   0.000      .0336273    .0725556
invests~2010 |    .022532   .0066503     3.39   0.002      .0088622    .0362018
   Incentive |     .11745   .0305735     3.84   0.001      .0546052    .1802949
       _cons |   .9008292   .0309826    29.08   0.000      .8371436    .9645148
```

Here: normal distribution exactly at prob> chi0.055

Annex Regression Results 3: Fixed and Random Effects Regression Results

```
. xtreg  F.patente    capacity_MW integr_dum experience if year < 2012 & year > 1990, re

Random-effects GLS regression                   Number of obs      =      1827
Group variable: id                              Number of groups   =        87

R-sq:  within  = 0.0984                         Obs per group: min =        21
       between = 0.3655                                        avg =      21.0
       overall = 0.1544                                        max =        21

                                                Wald chi2(3)       =    229.23
corr(u_i, X)   = 0 (assumed)                    Prob > chi2        =    0.0000

------------------------------------------------------------------------------
   F.patente |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
 capacity_MW |   .0177103   .0012046    14.70   0.000     .0153493    .0200713
  integr_dum |   .4372305   .2302184     1.90   0.058    -.0139892    .8884502
  experience |  -.0000596     .00009    -0.66   0.508    -.0002359    .0001168
       _cons |   .3914003   .1636005     2.39   0.017     .0707492    .7120514
-------------+----------------------------------------------------------------
     sigma_u |  1.2494313
     sigma_e |  2.8832961
         rho |   .1580923   (fraction of variance due to u_i)
------------------------------------------------------------------------------

. xtreg  F.patente    capacity_MW integr_dum experience if year < 2012 & year > 1990, fe

Fixed-effects (within) regression               Number of obs      =      1827
Group variable: id                              Number of groups   =        87

R-sq:  within  = 0.1023                         Obs per group: min =        21
       between = 0.0073                                        avg =      21.0
       overall = 0.0024                                        max =        21

                                                F(3,1737)          =     65.96
corr(u_i, Xb)  = -0.9992                        Prob > F           =    0.0000

------------------------------------------------------------------------------
   F.patente |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
 capacity_MW |   .0163145   .0012913    12.63   0.000     .0137819    .0188471
  integr_dum |  -.2690678   .2962144    -0.91   0.364    -.8500423    .3119066
  experience |  -.0294541   .0128741    -2.29   0.022    -.0547045   -.0042036
       _cons |   11.33342   4.746637     2.39   0.017     2.023697    20.64315
-------------+----------------------------------------------------------------
     sigma_u |  49.566701
     sigma_e |  2.8832961
         rho |  .99662766   (fraction of variance due to u_i)
------------------------------------------------------------------------------
F test that all u_i=0:     F(86, 1737) =     5.34            Prob > F = 0.0000

. xtreg  F.pat_cum    capacity_MW integr_dum experience if year < 2012 & year > 1990, re

Random-effects GLS regression                   Number of obs      =      1827
Group variable: id                              Number of groups   =        87

R-sq:  within  = 0.3449                         Obs per group: min =        21
       between = 0.2544                                        avg =      21.0
       overall = 0.2916                                        max =        21

                                                Wald chi2(3)       =    941.50
corr(u_i, X)   = 0 (assumed)                    Prob > chi2        =    0.0000

------------------------------------------------------------------------------
   F.pat_cum |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
 capacity_MW |   .1324273   .0045337    29.21   0.000     .1235414    .1413132
  integr_dum |   5.733275   .9524288     6.02   0.000     3.866549    7.600001
  experience |  -.0006125   .0007547    -0.81   0.417    -.0020917    .0008667
       _cons |   2.721741   1.314023     2.07   0.038      .146303    5.297179
-------------+----------------------------------------------------------------
     sigma_u |  11.366666
     sigma_e |  10.413288
         rho |  .54368949   (fraction of variance due to u_i)
------------------------------------------------------------------------------

. xtreg  F.pat_cum    capacity_MW integr_dum experience if year < 2012 & year > 1990, fe

Fixed-effects (within) regression               Number of obs      =      1827
Group variable: id                              Number of groups   =        87

R-sq:  within  = 0.3675                         Obs per group: min =        21
       between = 0.0080                                        avg =      21.0
       overall = 0.0049                                        max =        21

                                                F(3,1737)          =    336.36
corr(u_i, Xb)  = -0.9997                        Prob > F           =    0.0000

------------------------------------------------------------------------------
   F.pat_cum |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
 capacity_MW |   .1224493   .0046636    26.26   0.000     .1133025    .1315962
  integr_dum |   1.565402   1.069806     1.46   0.144    -.5328407    3.663644
  experience |  -.3656263   .0464961    -7.86   0.000    -.4568206    -.274432
       _cons |   137.4158   17.14292     8.02   0.000     103.7929    171.0387
-------------+----------------------------------------------------------------
     sigma_u |  615.41502
     sigma_e |  10.413288
         rho |  .99971377   (fraction of variance due to u_i)
------------------------------------------------------------------------------
F test that all u_i=0:     F(86, 1737) =    26.54            Prob > F = 0.0000
```

Annex Regression Results 4: Technological competitiveness and market formation

```
. regress  F.RPS_fam  standdevsize  policytarget   margininkwh2010 publicrd3yavin10mio20
> 10  investsupport3yavin10mio2010   Incentive if year < 2012 & year >1981

      Source |       SS       df       MS              Number of obs =      30
-------------+------------------------------           F(  6,    23) =   17.95
       Model |  .748315238     6  .124719206           Prob > F      =  0.0000
    Residual |  .159775493    23  .006946761           R-squared     =  0.8241
-------------+------------------------------           Adj R-squared =  0.7782
       Total |  .908090732    29  .031313474           Root MSE      =  .08335

------------------------------------------------------------------------------
    F.RPS_fam |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
standdevsize |   .0041107   .0011254     3.65   0.001     .0017826    .0064387
policytarget |   .0496315   .0711682     0.70   0.493    -.0975912    .1968542
margini~2010 |   .0133279   .0089634     1.49   0.151    -.0052144    .0318702
publicr~2010 |   -.027245   .0192398    -1.42   0.170    -.0670455    .0125556
invests~2010 |  -.0016843   .0097605    -0.17   0.865    -.0218755    .0185069
   Incentive |   .1194012   .0380945     3.13   0.005     .0405968    .1982056
       _cons |   1.077947   .1005792    10.72   0.000     .8698833    1.286011
------------------------------------------------------------------------------

. sktest resid

                   Skewness/Kurtosis tests for Normality
                                                         ------- joint ------
    Variable |    Obs   Pr(Skewness)   Pr(Kurtosis) adj chi2(2)    Prob>chi2
-------------+---------------------------------------------------------------
       resid |     32      0.6113         0.0485         4.29         0.1169

. vif

    Variable |       VIF       1/VIF
-------------+----------------------
standdevsize |      7.60    0.131542
publicr~2010 |      4.00    0.249785
margini~2010 |      3.60    0.277693
invests~2010 |      3.34    0.299524
policytarget |      2.76    0.361998
   Incentive |      2.12    0.471073
-------------+----------------------
    Mean VIF |      3.91

. hettest

Breusch-Pagan / Cook-Weisberg test for heteroskedasticity
         Ho: Constant variance
         Variables: fitted values of F.RPS_fam

         chi2(1)      =     0.14
         Prob > chi2  =   0.7122


. dwstat

Durbin-Watson d-statistic(  7,    30) =  2.471189

. ovtest

Ramsey RESET test using powers of the fitted values of F.RPS_fam
       Ho:  model has no omitted variables
                 F(3, 20) =      0.88
                 Prob > F =      0.4674
```

```
. regress  F.RPS_fam  standdevsize     margininkwh2010 publicrd3yavin10mio2010    Incent
> ive if year < 2012 & year >1981

      Source |       SS       df       MS              Number of obs =      30
-------------+------------------------------           F(  4,    25) =   28.31
       Model |  .743890056     4  .185972514           Prob > F      =  0.0000
    Residual |  .164200675    25  .006568027           R-squared     =  0.8192
-------------+------------------------------           Adj R-squared =  0.7902
       Total |  .908090732    29  .031313474           Root MSE      =  .08104

------------------------------------------------------------------------------
   F.RPS_fam |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
standdevsize |   .0043709   .0007353     5.94   0.000     .0028565    .0058853
margini~2010 |   .0142198   .0061693     2.30   0.030      .001514    .0269257
publicr~2010 |  -.0286753   .0153965    -1.86   0.074    -.0603851    .0030345
   Incentive |   .1154754   .0365959     3.16   0.004     .0401047     .190846
       _cons |   1.088764   .0567589    19.18   0.000     .9718669    1.205661
. sktest resid

                   Skewness/Kurtosis tests for Normality
                                                          ------- joint ------
    Variable |    Obs   Pr(Skewness)   Pr(Kurtosis)  adj chi2(2)    Prob>chi2
-------------+---------------------------------------------------------------
       resid |     32      0.7120         0.0944         3.20         0.2019

. dwstat

Durbin-Watson d-statistic(  5,    30) =  2.478285

. hettest

Breusch-Pagan / Cook-Weisberg test for heteroskedasticity
         Ho: Constant variance
         Variables: fitted values of F.RPS_fam

         chi2(1)      =     0.05
         Prob > chi2  =   0.8317



      Source |       SS       df       MS              Number of obs =      30
-------------+------------------------------           F(  4,    25) =   13.97
       Model |  .627383661     4  .156845915           Prob > F      =  0.0000
    Residual |  .280707071    25  .011228283           R-squared     =  0.6909
-------------+------------------------------           Adj R-squared =  0.6414
       Total |  .908090732    29  .031313474           Root MSE      =  .10596

------------------------------------------------------------------------------
   F.RPS_fam |      Coef.   Std. Err.      t    P>|t|                     Beta
-------------+----------------------------------------------------------------
PVCapacity~h |   .0612766   .0190986     3.21   0.004                 .6782448
margini~2010 |   .0255482   .0074128     3.45   0.002                 .4730746
publicr~2010 |  -.0189066   .0225352    -0.84   0.409                -.1719713
   Incentive |   .0648833   .0460009     1.41   0.171                  .217047
       _cons |   1.146915   .0840029    13.65   0.000                        .
```

no problems with serial correlation, heteroskedasticiy or multicollinearity

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Karlsruhe, August 2015