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Do policy mix characteristics matter for low-carbon innovation? A survey-based exploration of renewable power generation technologies in Germany

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ABSTRACT

Policy mixes may play a crucial role in redirecting and accelerating innovation towards low-carbon solutions, thus addressing a key societal challenge. Towards this end, some argue that the characteristics of such policy mixes matter greatly, yet with little empirical evidence backing up such claims. In this paper we explore this link between policy mix characteristics and low-carbon innovation, using the research case of the transition of the German electricity system towards renewable energy. Our empirical insights are based on an innovation survey administered to German manufacturers of renewable power generation technologies which builds on the Community Innovation Survey. For our purposes we adjusted the survey to better capture companies' perceptions of policy mixes. Employing a bivariate Tobit model we find evidence that companies' perceptions regarding the consistency and credibility of the policy mix are positively associated with their innovation expenditures for renewable energies, and this positive link intensifies when considering the mutual interdependence of these policy mix characteristics. In contrast, neither the comprehensiveness of the instrument mix nor the coherence of policy processes were found to be related to innovation expenditures. Overall, these findings suggest that future research on low-carbon and eco-innovation should pay greater attention to the characteristics of policy mixes, rather than focusing on policy instruments only. Finally, our findings indicate a need to consider how policy may be measured in innovation surveys to generate better informed policy advice regarding the greening of innovation.

1. Introduction

Achieving the ambitious decarbonization targets established by the Paris Agreement at COP21 in December 2015 requires the redirection and acceleration of innovation towards low-carbon solutions. As recognized by the OECD this implies that "*we need to ensure that we are talking about making all innovation green! To do that requires widespread adoption of the right support frameworks combined with clear and credible government commitments so that green considerations are incorporated into innovation policy settings from the outset*" (Guerría, 2016, p. 36). Similarly, the sustainability transitions literature calls for policy mixes which address the various market, structural and transformational system failures that hinder the much-needed decarbonization of the economy (Jacobsson and Bergek, 2011; OECD, 2015; OECD/IEA/NEA/ITF, 2015; Rogge et al., 2017; Rogge and Reichardt, 2016; Weber and Rohracher, 2012). There remain, however, large discrepancies between these acknowledgements of the importance of greening innovation and the need for policy mixes, and the mainstreaming of such thinking into innovation policy and research.

For such an endeavour, much can be learned from the literature on eco-innovation, which has long recognized the important role of policy in spurring green innovation (Bergek and Berggren, 2014; Díaz-García et al., 2015; Jaffe et al., 2002; OECD, 2011; Rennings, 2000). Building on the notion of "double externalities" that has emerged over the past two decades, both quantitative and qualitative studies have provided important insights into the measurement and determinants of eco-innovation (Bergek and Berggren, 2014; del Río, 2009; Kemp and Pontoglio, 2011; OECD, 2009). One of the key policy insights of this literature is that eco-innovation depends more on the design of a policy instrument than on its type, with environmental stringency standing out as a particularly relevant design feature (Frondel et al., 2008; Ghisetti and Pontoni, 2015). In addition, it has been acknowledged that eco-innovation benefits from the combination of demand pull and technology push instruments (Costantini et al., 2015; Peters et al., 2012) as well as systemic

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instruments (Cantner et al., 2016; Smits and Kuhlmann, 2004; Taylor, 2008; Wieczorek and Hekkert, 2012). However, broader policy mix aspects and in particular characteristics such as credibility, consistency and comprehensiveness have so far been addressed only rarely, with some notable recent advances using case studies and patent data (Costantini et al., 2017; Reichardt and Rogge, 2016).

Studies utilizing survey data have to the best of our knowledge not yet included such a broader approach to policy mixes in their questionnaire design and analysis, despite the methodological advantage of gathering more detailed policy data alongside other innovation measures. Yet, a recent review of econometric survey analyses shows that regulation is one of the few generally statistically significant determinants of eco-innovation (del Río et al., 2016). Because of limited data availability, however, the econometric models may capture the effect of a particular policy instrument by including a dummy variable only (del Río et al., 2016). In contrast, some specialized eco-innovation surveys have provided more in-depth insights into the link between policy and green innovation, such as through the inclusion of environmental policy stringency as a policy variable (Johnstone, 2007; Kammerer, 2009) or the simultaneous consideration of long-term targets and several climate, energy and innovation policy instruments (Schmidt et al., 2012). In contrast, large-scale innovation surveys, such as the Community Innovation Survey (CIS) conducted within the European Union, tend to cover policy to a limited extent, and often focus narrowly on public support for research and development (R&D), appropriation methods or obstacles to innovation. Similarly, the Oslo Manual, which provides guidelines for innovation surveys, puts little emphasis on the measurement of policy as a determinant of innovation, despite stressing the important policy guidance role of innovation survey data (OECD, 2005).

A notable exception to this apparent neglect of policy in mainstream innovation surveys is a question block on eco-innovation which was introduced as a supplement to the 2008 CIS wave, following suggestions made by the 'Measuring Eco-Innovation' (MEI) project (Kemp and Pearson, 2007). Since then, for participating countries such as Germany, Spain, Italy and France, information on eco-innovation and its drivers has been collected and analysed in these large-scale surveys, with (environmental) policy being explicitly included. Using the CIS survey as a key data source has made it possible to better understand the determinants of eco-innovation in general, and the role of policy in particular (Borghesi et al., 2015; Horbach et al., 2013; Rennings and Rammer, 2011). These studies have however not been able to address wider policy mix concerns, which is unlikely to change with the 2014 CIS wave, as the policy-related questions in the revamped eco-innovation block have remained largely unchanged (Rammer et al., 2016). Yet, given the urgency of climate change and other sustainability challenges we argue that the time has come to rethink how best to capture the link between policy and green innovation in innovation surveys.

In this paper, we take a first step in addressing this current shortcoming in mainstream innovation surveys by using the example of the decarbonization of the energy system, in which renewable energies play a key role (Gallagher et al., 2012; Jacobsson and Bergek, 2004; Negro et al., 2012). Given the supplier-dominated innovation pattern of the energy sector we focus on manufacturers of renewable power generation technologies (Pavitt, 1984; Rogge and Hoffmann, 2010). We limit the scope of our explorative study to the German *Energiewende* because of its ambitious targets and rich policy mix as well as its pioneering role in renewable energy innovation (Bruns et al., 2011; Pegels and Lütkenhorst, 2014; Quitzow et al., 2016; Strunz, 2014).

Building on recent qualitative insights into the impact of policy mix characteristics for innovation in the case of offshore wind power (Reichardt and Rogge, 2016) the aim of our paper is to quantitatively explore this link using survey data. In particular, we are interested in answering the research question whether policy mix characteristics indeed matter for innovation, and focus here on the four characteristics proposed by Rogge and Reichardt (2016): consistency, credibility, comprehensiveness and coherence (the 4Cs). For this, we build on the CIS questionnaire but redesign it to explicitly capture the current policy mix and low-carbon innovation. The resulting unique dataset collected in 2014 allows us to econometrically analyze the link between policy mix characteristics and green innovation, thereby supplementing patent-based evidence presented by Costantini et al. (2017), suggesting a key role of the comprehensiveness and balance of instrument mixes for patenting activity in energy efficiency. While our study concerns Germany, its insights provide research and policy implications which are also relevant to other regions and countries interested in harnessing the low-carbon market opportunities arising from the Paris Agreement, such as China, California, and the UK (Cai and Zhou, 2014; Anadon et al., 2014; Uyarra et al., 2016).

The remainder of the paper is structured as follows. In Section 2 we develop our analytical framework from the literature and derive hypotheses regarding the link between policy mix characteristics and innovation. Section 3 presents the research case of the German *Energiewende*. This is followed by Section 4, which introduces our methodological approach in terms of sampling, survey design, data collection and data analysis. In Section 5 we present our results, which we then discuss in Section 6. We conclude with policy and research implications in Section 7.

2. Analytical framework and hypotheses

Our interdisciplinary framework draws on environmental economics, innovation studies and policy analysis and follows the typical differentiation between firm-external and firm-internal determinants of eco-innovation (del Río, 2009). Regarding firm-external determinants we focus on the influence of a policy mix, thereby extending earlier work which has highlighted the role of environmental regulation and policy design features, such as stringency for eco-innovation (del Río et al., 2016). Here, we are particularly interested in answering the research question whether policy mix characteristics matter for low-carbon innovation. We therefore focus on the abovementioned four characteristics proposed by Rogge and Reichardt (2016), namely consistency, credibility, comprehensiveness and coherence (in short: the 4Cs). Such characteristics describe the nature of policy mixes and have been argued to affect the performance of policy mixes regarding standard assessment criteria, such as effectiveness and efficiency. As distinct bodies of literatures have used these terms quite differently, here we follow the definitions suggested by Rogge and Reichardt (2016) within their interdisciplinary policy mix framework (see Table 1).

First, we distinguish three levels of the *consistency* of the elements of a policy mix (Rogge and Reichardt, 2016). The first level concerns the consistency of the policy strategy and assesses the alignment of policy objectives, such as cost-effective deployment of renewables or the establishment of domestic manufacturing capacity, thereby capturing the extent to which these can be achieved simultaneously without significant trade-offs. Second, the consistency of the instrument mix captures whether instruments reinforce or instead undermine each other (Kern and Howlett, 2009). Third, the overall policy mix consistency captures the consistency of the instrument mix with the policy strategy, implying that they work together in a unidirectional or mutually supportive fashion (Howlett and Rayner, 2013).[1]

The literature suggests that a higher degree of consistency makes policy mixes more effective, for example by reducing the costs and risks associated with green R&D, or by increasing demand for environmentally friendly products and technologies. But the literature also recognizes the limits to policy mix consistency, particularly in

[1] The first and third levels of policy mix consistency relates to what the policy design literature refers to as goal 'coherence' and 'congruence' of goals and instruments (Howlett and Rayner (2013); Kern and Howlett (2009)).

Table 1
Definitions of the policy mix characteristics analyzed in this study.

Characteristic	Definition
Consistency	"captures how well the elements of the policy mix are aligned with each over, thereby contributing to the achievement of policy objectives. It may range from the absence of contradictions [weak consistency] to the existence of synergies [strong consistency] within and between the elements of the policy mix." (p. 1626)
Credibility	"the extent to which the policy mix is believable and reliable [.. .], both overall and regarding its elements and processes." (p. 1627)
Comprehensiveness	"captures how extensive and exhaustive [the elements of the policy mix are] and the degree to which its processes are based on extensive decision-making" (p. 1627)
Coherence	"referring to synergistic and systematic policy making and implementation processes contributing—either directly or indirectly—towards the achievement of policy objectives." (p. 1626)

Source: Rogge and Reichardt (2016).

transition processes (Quitzow, 2015a; Rogge and Reichardt, 2016). The role that consistency plays in innovation has so far been empirically explored mainly through qualitative studies. In the case of low-carbon innovation in the UK, Uyarra et al. (2016) find that the complexity and inconsistency of the UK innovation policy mix creates uncertainty among companies, thereby hampering private sector investment. Similarly, in the case of offshore wind power in Germany Reichardt and Rogge (2016) identify consistency as a key policy mix characteristic explaining innovation activities in the sector. They find that the consistency of the instrument mix, e.g. between feed-in tariffs and grid-access regulation, is particularly important for adoption decisions. In contrast, the overall consistency of the policy mix, in virtue of which the long-term target is substantiated by corresponding instruments, appears particularly crucial for research, development and demonstration (RD&D). This leads us to postulate a positive link between consistency and innovation:

Hypothesis 1. *The higher the consistency of a policy mix, the higher the level of innovation.*

Hypothesis 1.1. *The higher the consistency of a policy strategy (first-level policy mix consistency), the higher the level of innovation.*

Hypothesis 1.2. *The higher the consistency of an instrument mix (second-level policy mix consistency), the higher the level of innovation.*

Hypothesis 1.3. *The higher the consistency of a policy strategy with an instrument mix (third-level policy mix consistency), the higher the level of innovation.*

A second key characteristic of policy mixes is their *credibility*, which also may be key for innovation and can be influenced in a number of ways (Rogge and Reichardt, 2016). Clearly pointing in the direction of green innovation through unambiguous political signals, such credible policy mixes for low-carbon transitions may reduce the risks associated with long-term green investments and strengthen the prospects for future green market opportunities. In the case of energy, evidence suggests that whether political commitments are perceived as credible can influence investment and social outcomes (Nemet et al., 2014). Indeed, the role of the credibility of climate policy has attracted growing interest in climate economics, building on related work in monetary, fiscal and trade policy (Bosetti and Victor, 2011; Helm, 2003; Kang and Létourneau, 2016; Nemet et al., 2017). For example, in a model-based assessment Bosetti and Victor (2011) show that a lack of regulatory credibility has massive implications for costs because "firms and other agents become short-sighted and unable to make optimal investments in research and development as well as long-lived technologies" (p. 1).

Broadening this perspective to consider an overarching policy mix, Reichardt and Rogge's (2016) qualitative study of offshore wind power in Germany delivers further insights into the effects of credibility on investment and innovation decisions. They find that a credible policy strategy with ambitious, stable and technology-specific long-term targets stimulated firms' RD&D, and that the credibility of the overall policy mix facilitated adoption decisions. Similarly, a study of the corresponding technological innovation system supporting offshore wind power finds that policy mix credibility has a positive effect on guidance of the search, thereby stimulating innovation activities and overall system development (Reichardt et al., 2016). These insights lead us to postulate a positive link between policy mix credibility and innovation:

Hypothesis 2. *The higher the credibility of a policy mix, the higher the level of innovation.*

Recent qualitative research has also pointed to *interdependencies between policy mix characteristics, in particular between credibility and consistency*, but little is known about the nature of these interdependencies. For example, company case studies of German power generators, technology providers and project developers have shown that implementation through the EU emissions trading system as an additional instrument in the policy mix has significantly enhanced the credibility of long-term climate targets. That is, increasing the consistency of the instrument mix with long-term climate targets strengthened the credibility of these targets, thereby contributing to changes in corporate vision (Rogge et al., 2011).

In addition, in the cases of Ontario and Norway White et al. (2013) found that through abrupt changes in energy policy—to which they refer as temporal inconsistencies—governments lost political credibility, which in turn had negative impacts on low-carbon investments. However, White et al. stress that it is not temporal inconsistency per se but rather the manner in which policies are changed which is driving this effect. Arguably, the latter is related to the policy style and coherence of policy processes (Jänicke et al., 2000; Reichardt et al., 2017; Rogge and Reichardt, 2016). Based on these initial qualitative insights we postulate that interrelations between policy mix characteristics may affect their impact on innovation. In particular we explore whether the interdependence of credibility and consistency helps explaining the innovation impact of a policy mix:

Hypothesis 3. *The level of innovation depends on interdependencies between policy mix consistency and credibility.*

Third, regarding the *comprehensiveness* of the instrument mix the literature suggests that specific instruments are needed to address specific market and system failures associated with sustainability transitions (Weber and Rohracher, 2012), thereby making green innovation economically more attractive. For example, the creation of protected spaces for green niches may reduce uncertainties associated with market prospects for green innovation (Smith and Raven, 2012). Also, it has been argued that the elimination of multiple barriers facing renewable energy and energy efficiency requires the synergistic implementation of several policy instruments (Sovacool, 2009). Based on expert interviews Sovacool argues that the full potential of renewables and energy efficiency can be realized only through complementary instrument mixes. Similarly, but focusing on invention, the patent-based analysis of energy efficient technologies for the residential sector covering 23 OECD countries by Costantini et al. (2017) shows that the comprehensiveness of an instrument mix enhances innovation performance. However, they also find evidence for a threshold number of policy instruments included in the mix beyond which negative interaction effects may reduce the effectiveness of the policy mix in stimulating eco-innovation. In light of these considerations, we hypothesize a positive link between the comprehensiveness of an instrument mix and innovation.

Hypothesis 4. *The higher the comprehensiveness of an instrument mix, the higher the level of innovation.*

Finally, by including the *coherence of policy processes* in our analysis we aim to investigate the link between synergistic and systematic policy processes and innovation. The underlying assumption is that designing effective policy mixes requires policymakers to develop systematic capabilities as the basis for more coherent policymaking and implementation (Jacobsson and Bergek, 2011). For example, Quitzow (2015a) argues that governments require advanced organizational capacities, such as the ability to manage interfaces, assemble knowledge from diverse sources and establish constructive dialogues with all relevant stakeholder groups.

This need for strategic intelligence to facilitate change has also been discussed in the context of 'systemic instruments' (Smits and Kuhlmann, 2004). In addition, studies have identified multiple structural and procedural mechanisms which can strengthen policy coherence, such as strategic planning, communication and coordination (Ashoff, 2005; Den Hertog and Stroß, 2011; OECD, 1996, 2001). Of these, policy coordination has increasingly been discussed in the context of policy mixes (Magro et al., 2014), given both its potential for aligning tasks and efforts in the public sector (Bouckaert et al., 2010) but also recognizing its limits (Flanagan et al., 2011). However, the direct link between the coherence of policy processes and innovation has received little attention in empirical work. Yet, qualitative evidence in the case of offshore wind power in Germany suggests a positive effect of stakeholder participation and a negative effect of muddling through and uncertainties that arise from adaptive policy processes for innovation system functioning and performance (Reichardt et al., 2017). Jänicke et al. (2000) have previously highlighted the importance of policy style to innovation, identifying features such as dialogue and consensus, reliability and continuity, and openness and flexibility as innovation-friendly. Henceforth, we postulate that more synergistic and systematic policy processes positively contribute to innovation.

Hypothesis 5. *The greater the coherence of policy processes, the higher the level of innovation.*

Our analytical framework (see Fig. 1) includes not only policy mix characteristics such as firm-external determinants of innovation, but also both *technology push* and *demand pull* factors as classical determinants of innovation (Di Stefano et al., 2012; Mowery and Rosenberg, 1979). Given the strong relevance of policy in the context of low-carbon innovation, we focus on policy-driven technology push and demand pull, similar to what has been denoted as regulatory push and pull in the eco-innovation literature (Horbach, 2008). Extant empirical analyses typically find that both types of instruments matter for green innovation and work best in tandem (Costantini et al., 2015; Schleich et al., 2017; Schmidt et al., 2012; Veugelers, 2012). However, while the demand pull effect for export-oriented industries seems to result from a combination of demand at home and abroad, for technology push this positive effect seems to arise from public R&D support in the home market only (Dechezleprêtre and Glachant, 2014; Peters et al., 2012). Since this paper focusses on the role that policy mix characteristics play in encouraging innovation, other design features of specific instruments which have been found to affect innovation such as stringency (Ghisetti and Pontoni, 2015; Kemp and Pontoglio, 2011) are neglected.

Turning to the *firm-internal determinants of innovation*, we draw on insights from evolutionary economics and the resource-based view of the firm (Barney, 2001; Nelson and Winter, 1982; Wernerfelt, 1984). Because firm resources, capabilities and competencies matter for

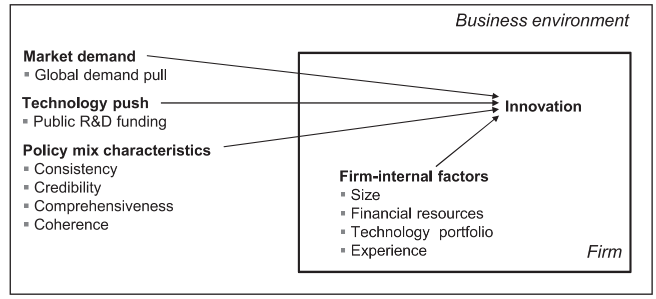

Fig. 1. Analytical frame work combining firm-external and firm-internal factors.

innovation, we include four key firm characteristics in our analytical framework (del Río et al., 2015; Helfat et al., 2007; Teece et al., 1997). The first concerns *firm size*, which has typically been found to affect eco-innovation positively (del Río et al., 2016; Kesidou and Demirel, 2012). In addition, we consider the availability of *financial resources* to be a prerequisite for green innovation (del Río et al., 2015, 2016). Our framework also considers a firm's *technology portfolio* to control for differences between renewable energy technologies and the relative importance of its green branch, as this may affect a firm's perceptions of and responses to policy stimuli (Huenteler et al., 2016; Schmidt et al., 2012). Finally, we include a firm's *experience* with using green technologies to capture accumulated resources as well as technological and organizational capabilities and competencies in using the respective green technology as drivers of innovation (Horbach et al., 2012; Kammerer, 2009).[2]

3. Research case

We have chosen to focus on innovation in renewable energy in Germany for three main reasons. First, we focus on renewable energy innovation as it is widely acknowledged that renewable energies, whose costs have dropped dramatically through green innovation, will play a key role in decarbonizing the global energy system (IEA and IRENA, 2017; IRENA, 2013). Second, we use the case of the *Energiewende* as Germany has implemented a rich policy mix with an ambitious policy strategy, including the long-term target of achieving at least an 80% share of electricity generated from renewable energies and reduction of greenhouse gas emissions by 80–95% by 2050. These targets are implemented through various instruments, such as the German Renewable Energy Sources Act (EEG) introduced in 2000 and dedicated public support for R&D to facilitate the decarbonization of the energy system (BMWi, 2015, 2016b; BMWi and BMU, 2010). Finally, given that innovation in the power sector has been dominated by suppliers we focus on the innovation activities of manufacturers of renewable power generation technologies, with Germany having a strong and export-oriented manufacturing base (Pavitt, 1984; Rogge and Hoffmann, 2010).

The German *Energiewende* has been the subject of substantive research reflecting a variety of (inter-)disciplinary and methodological approaches and analytical perspectives (Gawel et al., 2013; Geels et al., 2016; Hermwille, 2016; Kungl, 2015; Kuzemko et al., 2017; Matthes, 2017; Quitzow et al., 2016; Schmid et al., 2016, 2017; Smith Stegen and Seel, 2013; Strunz, 2014). Several studies have previously explored the link between policy and innovation, typically focusing on the role of the EEG as the core instrument in Germany's instrument mix, and specifically analyzing its design and co-evolution with technological and wider socio-technical change (Grau, 2014; Hoppmann et al., 2014; Lauber and Jacobsson, 2016). Attention has also been devoted to

[2] We refrain from using firm age as a factor reflecting the accumulation of internal green resources, capabilities and competencies, as firm age would not capture the diversification of incumbent firms into green technologies. Arguably, this may be one reason for the inconclusive empirical findings on the influence of firm age on green innovation (del Río et al. (2016)).

technology-specific analyses, such as for solar photovoltaic (PV; (Hoppmann et al., 2013; Quitzow, 2015b; Richter, 2013b) and wind power (Reichardt et al., 2017; Richter, 2013a; Schleich et al., 2017). In particular, in the case of offshore wind power, Reichardt et al. (2016) have addressed the role of the broader policy mix for green innovation, highlighting the relevance of policy mix characteristics (Reichardt et al., 2016; Reichardt and Rogge, 2016). Yet, to our knowledge, no quantitative study has yet explicitly addressed the role of the broader policy mix and its characteristics in innovation activities by means of survey data.

While analysis of German CIS data on eco-innovation is abundant (Horbach et al., 2012; Rexhäuser and Rammer, 2014), dedicated company surveys addressing the link between policy and low-carbon innovation in the German energy sector are rare. Two relevant exceptions are the studies of Schmidt et al. (2012) and Doblinger et al. (2015), who have surveyed, among other companies, also German manufacturers of renewable power generation technologies, in 2009 and 2012, respectively. For non-emitting technologies Schmidt et al. (2012) find that firms' perceptions of long-term climate targets, technology policies and expectations for the third phase of the EU emission trading system (EU ETS) are relevant to their R&D decisions. Doblinger et al. (2015) conclude that stronger demand pull policies reduce the implementation of high-risk R&D projects in favor of smaller improvements, a finding that was reinforced by perceived higher levels of regulatory uncertainty. Yet, neither study captures policy mix characteristics or follows a conventional innovation survey questionnaire.

The year before we fielded our survey was marked with a relatively high level of regulatory uncertainty. After the Fukushima accident in 2011 and the resulting reinstatement of the nuclear phase-out through 2022 (Hermwille, 2016), and with declining technology costs, particularly for solar PV installations (Hoppmann et al., 2014), the expansion of renewable energies in the German electricity system was accelerated in 2012 (BMWi, 2015). The resulting increases in the levy for the EEG surcharge led to debates over a retrospective adjustment of guaranteed feed-in tariffs (set for 20 years). Such a retrospective adjustment had previously been unimaginable. While they have not been implemented, these high-level suggestions may still have influenced the perceived predictability and associated investment security of the core demand pull instrument. In addition, given the federal elections in the fall of 2013, the next regular reform of the EEG was postponed until a new government coalition had been formed, leading to considerable uncertainty about the ambition of the *Energiewende* in general and especially about the future of the EEG.

Eventually, the new government merged all *Energiewende*-related activities under the roof of the new Federal Ministry of Economics and Energy (BMWi), which published a 10-point energy agenda providing a roadmap of the planned policy changes within the *Energiewende* due under the 18th legislative term. For example, this roadmap included policy mix–relevant items such as the EU ETS reform, electricity market reform, transmission and distribution grids and monitoring (BMWi, 2016a). A priority item was the revision of Germany's core demand pull policy, EEG, for which the BMWi published the first pillars at the beginning of 2014. However, the uncertainty over the design features of the EEG 2.0 remained fairly high until the Federal Cabinet adopted the amended Renewable Energy Sources Act on April 8, 2014.[3] Furthermore, regarding technology push policies, federal public R&D support for green innovation had risen above 800 million Euro per year by 2014, with a good third of this going to renewable energy and another third to energy efficiency (BMWi, 2016b). In the context of these policy mix developments the share of renewables in the German electricity system had reached 27.4% by the end of 2014, and was on track to meet the target of 40%–45% by 2025 (BMWi, 2014).

[3] The policy uncertainty was fully resolved after the approval by the Federal Parliament (Bundestag) on July 4, 2014.

4. Methodology

For our explorative study we generated a novel dataset based on a survey of German manufacturers of renewable power generation technologies (see Section 4.1). We began this process by compiling a company database (see Section 4.1.1), then designed a questionnaire which draws upon and extends the CIS (see Section 4.1.2) and finally collected company responses through a computer-assisted telephone survey (CATI, see Section 4.1.3). We close this section by presenting the econometric model and the variables used in our data analysis (see Section 4.2).

4.1. Innovation survey

4.1.1. Construction of company data base

Given the lack of a comprehensive database of companies producing components, final products or production equipment for electricity generation based on renewable energies, we drew on multiple data sources to compile such a database of all German manufacturers that are active in on- and offshore wind power, solar PV, hydro, bioenergy, wave and tidal energy, geothermal energy and concentrated solar power—whether or not they have carried out innovation activities in renewable energies. Because we focus on companies that are active in manufacturing our target group excludes companies that are involved solely in service provision, such as project management, finance, investments, installation, operations, maintenance, or sales.[4] Also, since our research question focuses on exploring the impact of the policy mix on innovation in renewable energies, we include in our sample only companies that offer products for this market.[5]

To compile this database we followed six steps.[6] First, we searched for manufacturers in four German business directories using their predefined, technology-specific search words reflecting the main components of each technology.[7] Second, we complemented the resulting list of companies by including member companies of the German Engineering Federation (VDMA) and technology-specific associations. Third, we further supplemented this list by searching for additional manufacturers in other publicly available sources, such as manufacturers listed in business fair catalogues and professional journals. Fourth, as a quality check we read companies' descriptions of their activities and searched their web pages to eliminate companies not fitting with our target group. Fifth, the resulting list was matched with sector-specific firm databases available to the SOKO research institute that conducted the survey (see 4.1.3). Finally, we used a screening question at the beginning of the survey to ensure that interviewed companies fit our search profile; those that did not were deleted from the sample.

As a result of this process we identified 1092 manufacturers that are active in producing components, equipment and final products for renewable power generation technologies in Germany (as of 2014). These companies were invited to participate in a computer-assisted telephone interview, as detailed in 4.1.3.

4.1.2. Questionnaire design

Notwithstanding the limitations of cross-sectional data, two main options exist for exploring the link between policy and innovation in a one-off

[4] In contrast, the sample (140 out of 1,208) compiled by Doblinger et al. (2015) includes not only manufacturers but also project developers that are active in renewable energies in Germany.

[5] Our sample includes manufacturers which sell only renewables and manufacturers with more diversified portfolios (for some manufacturers, renewables account for only 1% of total turnover).

[6] To give our sample of companies a broad scope, we decided not to use patents to identify the population. In addition, because of the time lag in patent statistics, companies which recently entered the renewable energy field would not have been included. This decision was confirmed by the answers submitted by the companies participating in our sample. When asked how they protect intellectual property, only 43.8% indicated that they use patents, whereas other strategies such as confidentiality (71.2%) and lead-time advantages over competitors (60.4%) appeared to be more important (based on 386 responses; multiple answers were possible).

[7] The four directories utilized were: "Wer liefert was" (WLW), businessdeutschland.de (BD), diedeutscheindustrie.de (DDI), and Hoppenstedt (HS).

survey. First, questions can inquire directly into the relevance of political factors to past innovations, as was done, for example, in the eco-innovation module of the CIS. In this case, only innovators can be analyzed (Ziegler, 2013). In addition, insofar as innovation questions typically inquire into the past three years this assumes that respondents remember the policy mix of the past and how it influenced past innovation decisions. Such an assumption seems problematic, with perceptions likely being blurred and influenced by more recent developments in the policy mix. The second and methodologically preferable option is to ask companies separately for their perceptions of the current policy mix and—in a distinct question block—their current (and expected) innovation activities and/or expenditures, as it is these efforts which today's policy mix may influence and which will be largely known at the time of the survey.[8] In this paper, we pursue the second option and employ multivariate regression analysis to explore the correlations between innovation efforts and the policy mix.

Our questionnaire is based on the (German) CIS, as it represents an established tool for measuring corporate innovation activities, which, however, includes only a few items on policy and does not capture policy mix thinking. Since our research focuses on the link between policy mix characteristics and innovation we therefore designed novel supplementary questions on the policy mix and its consistency, credibility, comprehensiveness and coherence (see Table 2). These questions build on the policy mix concept proposed by Rogge and Reichardt (2016) and ask for subjective perceptions rather than objective facts, as perceptions are typically assumed to govern agents' behavior (Kaplan and Tripsas, 2008; Nooteboom, 2009; Schmidt et al., 2012). Three industry experts—one each in the fields of solar PV, wind power and renewable energies more generally—provided feedback on our draft question design.[9]

The resulting questionnaire consists of six parts.[10] It starts with a section on general information about each company. This section draws on the CIS but also includes questions pertaining to each firm's product portfolio regarding renewable power generation technologies and the selection of its main product, about which respondents' are asked to answer the remaining questions in the survey to gather technology-specific information. The second part represents the novel block of questions on the policy mix which addresses companies' perceptions of political targets and their consistency, the consistency and comprehensiveness of the instrument mix and perceived support by various policy instruments, and selected design features of the core demand pull instrument EEG (Renewable Energy Sources Act) and technology push support. In addition, the policy mix block includes questions about the policymaking process to capture its coherence, and closes with questions on the credibility of the policy mix.

In line with the CIS the third part asks about innovation, innovation activities and innovation expenditures—again with a focus on each firm's main renewable power generation technology—and also includes extended questions on innovation objectives and political factors for innovating (or not). In the fourth part, the questionnaire collects information on the market environment regarding the main renewable energy technology, such as geographic markets, input and sales price developments, and further characteristics of the competitive environment, which again draw largely on the CIS. The same is true for the fifth part, which captures general economic information, such as the number of employees, turnover and exports, but also addresses the expansion of production facilities. The questionnaire closes with a final section asking about the interviewee's position, an open question regarding recommendations for the German government, and respondents' willingness to be approached in a follow-up survey.[11]

4.1.3. Survey implementation

The survey was implemented by an experienced research institute, SOKO.[12],[13] All companies in our database of manufacturers were first contacted by a postal letter explaining the rationale and sponsor of the study. This letter also included a flyer providing further background information and a link to the overarching project website.[14] After this, each company was contacted via phone to arrange for an interview appointment with the CEO or a top-level manager responsible for the company's strategy, R&D or sales and with an overview of products, innovation and corporate policy. The survey was fielded from April 9, 2014 until July 22, 2014 and was answered by 390 companies, yielding a response rate of 35.7% of all German manufacturers of renewable power generation technologies.[15] On average, these phone interviews were 30 min in length. SOKO anonymized all data for further processing. The descriptive results of the survey were compiled in a report which was sent to participating companies (Rogge, 2015).

The results show that approx. 70% of respondents are small and medium-sized enterprises (SMEs). More than half of the responses concerned solar PV (37.2%), biogas (22.3%) and onshore wind power (17.4%). In addition, 71% of respondents produce components for renewable power generation technologies (see Figs. A1 and A2 in Appendix A). In 2013, only 11.1% of companies operated exclusively in the German market; on average 39.5% of sales were exports. Most companies were innovative, with 82% of respondents engaging in innovation activities in the last three years (2011–13). In addition, three quarters of the companies introduced product innovations in this period (75%) and two-thirds introduced process innovations (66%) for the selected renewable power generation technology. About a quarter of the respondents received public R&D funding (from Germany or the EU) to pursue innovation activities in the main renewable power generation technology in the period 2011–13.

4.2. Econometric model

4.2.1. Dependent variable

For our dependent variable we employ innovation expenditures as an input measure of innovation. The survey asked respondents to provide estimates for innovation expenditures for each company's main renewable power generation technology in 2014 and 2015.[16] About 25.6% (n = 348) reported innovation expenditures of zero for 2014. For 2015 this share was 31.3% (n = 272). Thus, for a substantial portion of the companies in our survey, the stated innovation expenditures in one or both years equal zero. We therefore employ the "corner solution" Tobit model to specify the regression equation for innovation expenditures in a particular year (y). Relying on the "latent variable"

[8] In contrast, resulting innovations will still be uncertain at the time of the survey, as not all of the inputs into the innovation process will lead to innovation outputs in terms of new or significantly improved products or processes.

[9] Our questionnaire reflects two further changes regarding the (German) CIS. First, we tailored the questionnaire to our renewable energies research case. For example, we asked companies for their product portfolios regarding renewable power generation technologies and their technology-specific innovation expenditures and turnover. And second, we adapted the written language to the context of a phone interview situation. For example, we repeated the question in the middle of a long list of items to remind respondents of the original question and provided definitions for what is meant by certain terms, such as 'innovation'.

[10] Note that the following is a summary of the full innovation questionnaire. Only part of the collected information is needed for our analysis.

[11] The original German questionnaire (and its translation into English) is available in the supplementary material to this article.

[12] http://www.soko-institut.de/

[13] After programming the questionnaire as a CATI it was tested in SOKO's facilities with two researchers present. This live test lasted one day and covered interviews with companies active in distinct technologies. These pre-tests confirmed the survey design and resulted in only minor adjustments.

[14] Any company with an email address also received this information via email.

[15] To test for sampling bias, the data enabled us to examine the regional representativeness of our sample. The shares of participants per federal state in the sample are very close to the share of all companies per federal state in the population. Based on a χ^2 test we find no indication that our sample may suffer from sampling bias ($p > 0.99$).

[16] Respondents were asked about their expenditures for their innovation activities (including intramural—in-house—and extramural R&D, acquisition of machinery, equipment and software, acquisition of other external knowledge, and other preparation).

Table 2
Operationalization of variables for policy mix characteristics.

Policy mix characteristics	Statement (translated from German to English) (response categories ranging from 1 (do not agree at all) to 6 (fully agree))	Variable name
Consistency		
1st level: consistency of the policy strategy	The planned expansion target for renewable energies in Germany up to 2025 is a good match with other energy and climate policy targets of the German government.	*Consistency1_PS*
2nd level: consistency of the instrument mix	The existing policy instruments reinforce each other in their positive effect on supporting the expansion of renewable energies.	*Consistency2_IM*
3rd level: consistency of the instrument mix with the policy strategy	The planned expansion target for renewable energies in Germany up to 2025 can be achieved with the help of existing policy instruments and measures.	*Consistency3_PM*
Credibility	Concerning the increase in electricity generation based on renewable energies in Germany, there is. . .	
Policy mix credibility at the national level	a broad consensus across all political parties a clear political vision a firm political will unambiguous political signals strong support from the German government	*Credibility_national*
Policy mix credibility at the sub-national level	strong support from Federal States strong support from municipalities	*Credibility_subnational*
Comprehensiveness	Important flanking policies are missing that push the expansion of renewables (e.g. on power market design or for grid expansion)	*Comprehensiveness*
Coherence		
Informational coherence	There is a continuous exchange of information between policymakers and manufacturers. Policymakers are well informed about developments in the branch. Emerging problems are spotted early on by policymakers. Policymakers always strive to remove obstacles. The search for solutions to problems takes place in a constructive exchange between policymakers and representatives of the RE branch.	*Coherence_informational*
Procedural coherence	The last amendments of the EEG (2012 and today) were made in a transparent procedure. The responsibilities for the branch are clearly defined for the relevant Federal ministries. National and Federal State governments are pulling in the same direction.	*Coherence_procedural*

approach, truncation (from below) is motivated by

$$y_i^* = \beta_0 + \beta_1(TechPush_i) + \beta_2(DemandPull_i) + \beta_3(PolicyMix_i) + \beta_4(Controls_i) + u_i;$$
$$u_i \sim N(0, \sigma^2) \tag{1}$$

$$y_i = y_i^* \ if \ y_i^* \geq 0$$
$$y_i = 0 \ if \ y_i^* < 0$$

where y_i^* stands for the latent (i.e. desired) level of innovation expenditures of firm *i* in a given year. To test our hypotheses and account for other factors related to firms' innovation expenditures, we include four groups of explanatory variables capturing: (i) the effects of market demand, and in particular global demand pull effects (*DemandPull*); (ii) public funding for technology push (*TechPush*); (iii) the effects of policy mix characteristics (*PolicyMix*); (iv) and the effect of control variables to reflect company- and technology-specific effects (*Controls*). Thus, positive values for innovation expenditures are observed if the latent variable y* exceeds the threshold level of zero[17]; otherwise companies chose not to spend money on innovation.

Rather than estimating (1) separately for 2014 and 2015 via univariate Tobit models, we employ a bivariate Tobit model to estimate innovation expenditure equations, where the error terms capture possible correlations between innovation expenditures in different years. That is, the use of univariate Tobit models could lead to biased and inconsistent parameter estimations (Greene, 2012). The simulated maximum likelihood estimations are carried out with Stata 13, relying on Barslund (2009).

4.2.2. Explanatory variables

The set of explanatory variables consists of variables reflecting demand pull and technology push, policy mix characteristics, and firm-internal factors.

For *demand pull* we relied on a dummy variable *(DemandPull)*, which takes the value of one if the respondent expected the sum of domestic sales and exports of the main technology in 2014 to be higher than in 2013 and zero otherwise. This variable can be interpreted as a proxy for the effect of global demand pull instruments because of the strong dependence of market demand for renewable power generation technologies on such instruments (Dechezleprêtre and Glachant, 2014; Hoppmann et al., 2013; Peters et al., 2012).

For *technology push*, we focus on public R&D funding in the home market (Peters et al., 2012), which arguably for most of the companies in our sample is Germany (n = 360) and Europe (n = 333). Therefore, we use the amount (in Euros) of public subsidies for R&D each company had received between 2011 and 2013 from German or EU funding bodies for the main technology (*TechPush*).

For the variables employed for policy mix characteristics we distinguish between consistency, credibility, comprehensiveness and coherence (Rogge and Reichardt, 2016). For *consistency* of the policy mix we differentiate between three levels of consistency: Our explanatory variable for the first-level consistency of the policy strategy (PS) is constructed by first calculating the median value of the responses to the statement presented in Table 2. *Consistency1_PS* is coded as one if the response category was at least as high as the median value and zero otherwise. In the same way we calculate indicators for the second-level consistency of the instrument mix (IM) (*consistency2_IM*) and third-level consistency of the overarching policy mix (PM), i.e. of the instrument mix with the policy strategy (*consistency3_PM*). Thus, higher values of the consistency variables indicate higher consistency of the policy strategy, of the instrument mix, and of the instrument mix with the policy strategy.

To construct our explanatory variables capturing *credibility* (and to make a parsimonious model specification possible) we first conducted a standard principal component factor analysis (using varimax rotation) on the items shown in Table 2 under the subheading 'credibility' (Cronbach's alpha = 0.81, indicating good scale reliability). As a result of the factor analysis, two factors were kept (with eigenvalues

[17] Note that the threshold level is arbitrary since it is always possible to normalize. For example, a negative parameter estimate for β_0 would indicate a positive threshold level.

Table 3
Descriptive statistics of dependent and explanatory variables.

Variables	Unit	Number of observations	Mean	Standard deviation	Minimum	Maximum
*Innovation expenditures 2014**	in 1000 Euros	315	2,023	15,600	0	250,000
*Innovation expenditures 2015**	in 1000 Euros	244	1,587	7,958	0	75,000
DemandPull	dummy	376	0.40	0.49	0	1
*TechPush**	in Million Euros	387	46.6	245	0	2,000
Consistency1_PS	dummy	375	0.73	0.45	0	1
Consistency2_IM	dummy	380	0.72	0.45	0	1
Consistency3_PM	dummy	382	0.68	0.47	0	1
Credibility_national	score	387	0.75	0.33	0	1
Credibility_subnational	score	369	0.70	0.38	0	1
Comprehensiveness	dummy	384	0.69	0.46	0	1
Coherence_informational	score	385	0.70	0.34	0	1
Coherence_procedural	score	384	0.64	0.36	0	1
*Size (sales)**	in Million Euros	314	239	901	0.15	10,000
Financial resources	in 1000 Euros per employee	313	829.66	5,286.08	0.25	7,000
*Experience**	years	380	14.11	11.36	0	64
Wind	dummy	387	0.24	0.43	0	1
RE_share	in %	344	51.18	38.01	0.04	100

* The natural logarithm is used in the econometric estimation[19].

exceeding 0.9)—with policy mix credibility at the national level explaining 50% of the total variance and policy mix credibility at the subnational level (i.e. Federal states and municipalities) explaining 17%, respectively. Based on the factor loadings, we then construct two indicators, *Credibility_national* and *Credibility_subnational*, by taking the means of the binary variables of the individual items. These binary variables were coded as one if the response category was at least as high as the median value and zero otherwise.

Our explanatory variable reflecting the *comprehensiveness* of the instrument mix was constructed in the same manner as the consistency variables. That is, we first calculated the median value of respondents' responses to the respective statement presented in Table 2 under the subheading ‘comprehensiveness’. *Comprehensiveness* is then coded as one if the response category was at least as high as the median value and zero otherwise. Thus, all coefficients capturing the characteristics of the policy mix are expected to exhibit a positive sign.

Finally, our explanatory variables for the *coherence* of policy processes were constructed in a similar way as those for credibility. Based on the results of a standard principal component factor analysis (using varimax rotation) on the items shown in Table 2 under the subheading ‘coherence’ we keep two factors, explaining 47% (informational coherence) and 14% (procedural coherence) of the total variance, respectively (Cronbach's alpha = 0.82). We then construct two indicators, *Coherence_informational* and *Coherence_procedural*. To do so we again take the means of the binary variables of the individual items. Again, binary variables were coded as one if the response category was at least as high as the median value and zero otherwise.

Regarding the four firm-internal factors included in our analytical framework we proceeded as follows. First, *size* is measured by the total sales of each firm in 2013 in domestic and foreign markets (i.e. for diversified firms this includes business fields other than the main renewable energy technology). Second, *financial resources* are proxied by the ratio of sales per employee, which reflect the resources a firm may mobilize to finance R&D. Third, *experience* is measured as the number of years each firm had been offering products for the main renewable power generation technology (measured against 2014). Finally, we capture each firm's technology portfolio with two explanatory variables: The first is *wind* and takes the value of one if a firm's responses referred to either onshore or offshore wind and zero otherwise.[18] The second is *RE_share*, which captures the share of employees working in the main renewable power generation technology in 2013 relative to all employees. Table 3 presents the descriptive statistics on the variables used in the econometric analysis.

5. Results

Our econometric analysis involves estimating several model specifications, reflecting the hypotheses derived in Section 2. The results appear in Table 4. Heteroskedasticity-robust p-values are shown in parentheses below the parameter estimates. For lack of degrees of freedom we do not start with a model which includes all explanatory variables in the same specification.

5.1. Base model

As a first step, we estimated a *base model*, which includes *DemandPull, TechPush*, and *Controls* as explanatory variables, thus abstracting from any policy mix characteristics. Table 4 presents the results of this base model in the first set of columns. We find that the correlation is high and positive between the two equations ($\rho = 0.926$), and statistically significant.[20]

In general, all coefficients in the base model exhibit the expected signs and are almost all statistically significant.[21] In particular, the findings confirm the positive relationship of global demand pull and European technology push effects with innovation expenditures in 2014 and 2015.[22] Calculating the marginal effect for *TechPush* in the R&D

[18] Including dummies for other renewable energy technologies produced coefficients which were far below statistical significance. To save degrees of freedom, we incorporated only *wind*.

[19] Since the logarithm of zero is not defined, using the logarithm meant losing one observation (where *size* was zero). No observation in our final sample had zero *experience*. When public R&D (*TechPush*) or *innovation expenditures* were zero, we assigned the value of zero to the undefined logarithm. Since all positive *innovation expenditures* in 2014 and 2015 were above 1000 Euros, taking the logarithm did not lead to negative values for the dependent variables.

[20] Based on a Likelihood-Ratio test, the Null Hypothesis ($\rho = 0$) can be rejected at $p < 0.01$ ($\chi^2(1) = 307.686$).

[21] We calculated variance inflation factors (VIF) to explore whether collinearity may be a problem. Using all explanatory variables employed in this and subsequent specifications, the average VIF is 2.22. All VIFs of the individual variables (including are *Cons3 X Cred_nat) are* below 10. Thus, our parameter estimates do not appear to suffer from collinearity.

[22] We ran an additional base model allowing *TechPush* and *DemandPull* to interact. While the coefficient of this interaction term took on the expected positive sign, the p-values were quite high (0.80 and 0.74). Otherwise, the findings were virtually the same as those obtained from the base model, but the AIC and BIC values were somewhat higher, i.e. 1894 for AIC and 1964 for BIC.

2014 equation suggests that on average a one-percent increase in public subsidies for R&D received for a manufacturer's main renewable power generation technology between 2011 and 2013 is associated with a 0.158 percent increase in firm-level innovation expenditures in 2014 for firms with positive innovation expenditures in 2014.[23]

Larger firms (in terms of sales) and firms with greater financial resources (in terms of sales per employee) are related to higher innovation expenditures in 2014 and 2015. For example, for firms with positive innovation expenditures in 2014 a one-percent increase in sales or sales per employee is associated with an increase in innovation expenditures in 2014 of about 0.652 percent and 0.047 percent, respectively. In addition, firms active in wind technologies are associated with statistically significantly higher innovation expenditures in 2014 and 2015 compared with firms that focus on other renewable electricity technologies, indicating strong differences across technologies. Furthermore, the coefficient associated with the share of employees working in the main renewable power generation technology turns out to be significant at conventional levels of significance for 2014 only. Finally, more experienced firms (in terms of years being active in the main renewable power generation technology) spend more on innovation, but for 2014 the coefficient is just shy of statistical significance.[24]

Next, we employ several models to test the effects of policy mix characteristics on innovation expenditures. We first note that for these models the coefficients of the variables included in the base model are very similar to those of the base model, i.e. they are barely affected by including the additional policy mix variables; however, model quality tends to improve, as indicated by smaller AIC and BIC values.

5.2. Consistency models

We start by testing the effects of the *consistency* of the policy mix on innovation expenditures. To do so we first extend the base model to include our variables for the three levels of consistency individually and then in combination. The estimation results for the individual models suggest that *Consistency1_PS (*consistency of the policy strategy) exhibits the expected positive sign but is not statistically significant, leading us to reject hypothesis 1.1. In comparison, the coefficients for *Consistency2_IM* (consistency of the instrument mix) and *Consistency3_PM* (consistency of the instrument mix with the policy strategy, i.e. the overarching policy mix) are, as expected, positive in both equations, and are also statistically significant—except for the 2014 innovation expenditure equation, where *Consistency_level2* is significant only at p = 0.134. However, when the variables for all three consistency levels are included simultaneously, only *Consistency3_PM* turns out to be statistically significant for innovation expenditures in 2015 (for 2014 *Consistency3_PM* becomes significant at $p < 0.155$). Most likely, this loss in significance is due to the loss in degrees of freedom. In summary, these findings provide weak support for hypothesis 1.2 and strong support for hypothesis 1.3.

5.3. Credibility models

To explore the impact of the *credibility* of the policy mix on innovation expenditures we included our two indicators derived from the factor analysis in the base model. As in our step-wise procedure for consistency we start with two separate models for *Credibility_national* (policy mix credibility at the national level) and *Credibility_subnational* (policy mix credibility at the sub-national level) and find both to be positively related to innovation expenditures and also statistically significant in both equations. However, when we include both credibility variables the coefficients associated with *Credibility_national* and *Credibility_regional* are just shy of statistical significance.[25] In sum, our results weakly support hypothesis 2.

In addition, we allowed for possible interaction between consistency and credibility. More specifically, we included an interaction term for third-level consistency of the overarching policy mix (i.e. consistency between the instrument mix and the policy strategy) and national credibility (*Cons3 X Cred_nat*) together with *Consistency3_PM* and *Credibility_national.*[26] The interaction term turns out to be negative and statistically significant for innovation expenditures in 2015 (for 2014, p = 0.245, hence above conventional levels). At the same time, the coefficients for *Consistency3_PM* and *Credibility_national* remain positive and statistically significant for both years (with the exception of *Credibility_national* in 2014 at p = 0.149). Thus, *Credibility_national* has a larger positive effect on R&D expenditures if *Consistency3_PM* is low. Likewise, *Consistency3_PM* has a larger positive effect on R&D expenditures if *Credibility_national* is low.[27] Thus, at low levels of one of these policy mix characteristics the effect of the other policy mix characteristic on R&D expenditures is larger, suggesting some degree of substitution between the two policy mix characteristics. This provides supporting evidence for our third hypothesis positing interdependencies between consistency and credibility.

5.4. Comprehensiveness model

Our model addressing the comprehensiveness of the instrument mix shows that the coefficient of *comprehensiveness* is positive for innovation expenditures in 2014 and 2015, but lacks statistical significance, leading us to reject hypothesis 4.

5.5. Coherence model

In our model capturing the *coherence* of policy processes the coefficients of the indicators capturing informational and procedural coherence both exhibit the expected positive sign for innovation expenditures in 2014 and 2015. However, the coefficients are not statistically significant.[28] Thus, for the sample at hand, we do not find empirical support in favor of hypothesis 5.

5.6. Overall model

Finally, we estimate the full model, which includes all explanatory variables, and in particular all four policy mix characteristics (the 4Cs)—once with and once without the interaction term for credibility and consistency. The results are very similar to those obtained for the individual models, but significance levels for the coefficients tend to be inferior, most likely due to lower degrees of freedom. As a consequence, unlike in the individual models, the coefficients associated with policy mix credibility are no longer statistically significant at conventional levels. In general though, the findings of the 4C model and the individual models are largely consistent, suggesting that any potential omitted variable bias in the individual models is negligible.

[23] Consistent marginal effects were derived from running a single Tobit model for innovation expenditures in 2014.

[24] We ran additional analyses to control for other company-specific effects. Including dummy variables for other renewable energy technologies (PV, hydro power, or biomass), or including a dummy variable for small and medium-sized enterprises hardly affects the findings presented but lowers the degrees of freedom. Since the coefficients associated with these variables are all far from being statistically significant, they are not included in the subsequent analyses.

[25] P-values of the four coefficients range between 0.11 and 0.19.

[26] Since policy mix consistency was assessed at the national level, we chose policy mix credibility at the national level to interact with policy mix consistency.

[27] In a separate model, we also allowed *Consistency2_IM* (i.e. the consistency of the instrument mix) and *Credibility_national* to interact. The coefficient was negative in both equations, but not statistically significant (p > 0.2 in both equations).

[28] For completeness, we also ran two models where the coherence variables entered singularly rather than in combination. In these cases all coefficients associated with *Coherence_informational* and *Coherence_procedural* were positive but failed to be statistically significant. The p-values of the four coefficients ranged between 0.13 and 0.30.

Table 4
Regression results.

Variable	*Base model*		*Consistency1_PS*		*Consistency2_IM*		*Consistency3_PM*		*Consistency_all*		*Credibility_national*	
	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015
DemandPull	2.843***	4.932***	2.782***	4.911***	2.898***	4.878***	2.632***	4.613***	2.780***	4.774***	2.494***	4.461***
	(0.001)	(0.000)	(0.002)	(0.000)	(0.001)	(0.000)	(0.002)	(0.000)	(0.002)	(0.000)	(0.005)	(0.000)
TechPush	0.224**	0.224*	0.233**	0.233*	0.241**	0.256**	0.205**	0.190*	0.217**	0.210*	0.251***	0.262**
	(0.016)	(0.054)	(0.015)	(0.053)	(0.016)	(0.036)	(0.024)	(0.085)	(0.034)	(0.089)	(0.007)	(0.024)
Size	0.919***	0.999***	0.908***	0.991***	0.936***	1.007***	0.884***	0.932***	0.915***	0.973***	0.925***	1.006***
	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)
Financial resources	0.048*	0.084***	0.044*	0.081**	0.047*	0.082***	0.043*	0.076**	0.042*	0.076**	0.039	0.072**
	(0.053)	(0.009)	(0.086)	(0.015)	(0.055)	(0.010)	(0.076)	(0.016)	(0.091)	(0.019)	(0.117)	(0.026)
Wind	2.698***	2.376*	2.669***	2.385*	2.227**	1.675	2.055**	1.380	1.905**	1.209	2.319**	1.872
	(0.005)	(0.053)	(0.007)	(0.064)	(0.019)	(0.162)	(0.029)	(0.239)	(0.048)	(0.314)	(0.015)	(0.125)
RE_share	2.554*	2.488	2.830*	2.786	2.462*	2.358	2.798**	2.904	2.807*	2.828	2.892**	2.927*
	(0.074)	(0.163)	(0.055)	(0.132)	(0.081)	(0.178)	(0.050)	(0.102)	(0.054)	(0.120)	(0.036)	(0.090)
Experience	1.145*	1.266	1.095*	1.216	1.072*	1.191	1.266**	1.475*	1.117*	1.320*	1.157*	1.295*
	(0.060)	(0.105)	(0.076)	(0.127)	(0.071)	(0.116)	(0.034)	(0.053)	(0.061)	(0.084)	(0.052)	(0.090)
Consistency1_PS			0.858	0.717					0.284	−0.236		
			(0.435)	(0.602)					(0.794)	(0.859)		
Consistency2_IM					1.687	2.770*			0.819	1.586		
					(0.134)	(0.056)			(0.534)	(0.337)		
Consistency3_PM							2.198**	3.645**	1.801	3.011*		
							(0.047)	(0.011)	(0.155)	(0.058)		
Credibility_national											2.961*	4.088**
											(0.054)	(0.036)
Credibility_subnational												
Cons3 X Cred_nat												
Comprehensiveness												
Coherence_informational												
Coherence_procedural												
Constant	−13.497***	−17.196***	−13.987***	−17.687***	−14.672***	−18.859***	−14.451***	−18.704***	−15.174***	−19.573***	−15.798***	−20.389***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Log (Pseudo) likelihood (χ^2)	-926.056 (96.06)***		-906.207 (98.08)***		-915.778 (110.85)***		−919.905 (122.12)***		−891.867 (126.94)***		−923.434 (103.02)***	
Rho (χ^2)	0.926 (307.686)***		0.926 (300.651)***		0.922 (296.319)***		0.923 (299.813)***		0.922 (285.744)***		0.924 (303.919)***	
AIC	1890.111		1854.415		1873.557		1881.810		1833.735		1888.868	
BIC	1953.062		1923.574		1942.926		1951.284		1915.688		1958.446	
Observations	203		199		201		202		196		203	

(*continued on next page*)

Table 4 (*continued*)

Variable	*Credibility_subnational*		*Credibility*		*Cons3 X Cred_nat*		*Comprehensiveness*		*Coherence*		*4C (no interaction)*		*4C (full model)*	
	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015
DemandPull	3.509***	6.321***	3.189***	5.816***	2.571***	4.688***	2.915***	5.020***	2.729***	4.752***	3.457***	6.038***	3.622***	6.376***
	(0.000)	(0.000)	(0.001)	(0.000)	(0.004)	(0.000)	(0.001)	(0.000)	(0.003)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
TechPush	0.203**	0.253*	0.225**	0.292**	0.227**	0.219*	0.216**	0.210*	0.224**	0.223*	0.189*	0.224	0.183*	0.213
	(0.034)	(0.078)	(0.017)	(0.042)	(0.015)	(0.056)	(0.020)	(0.069)	(0.019)	(0.057)	(0.081)	(0.164)	(0.089)	(0.186)
Size	0.929***	1.186***	0.929***	1.185***	0.910***	0.977***	0.913***	0.991***	0.895***	0.959***	0.953***	1.162***	0.971***	1.196***
	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)
Financial resources	0.040	0.075**	0.033	0.065*	0.042*	0.079**	0.044*	0.077**	0.049*	0.085**	0.040	0.072*	0.045*	0.083**
	(0.102)	(0.046)	(0.170)	(0.084)	(0.091)	(0.015)	(0.082)	(0.018)	(0.058)	(0.013)	(0.124)	(0.069)	(0.094)	(0.046)
Wind	2.174**	2.344	1.900*	1.907	1.985**	1.304	2.699***	2.369*	2.695***	2.372*	1.654	1.294	1.687	1.355
	(0.029)	(0.126)	(0.057)	(0.212)	(0.035)	(0.268)	(0.005)	(0.053)	(0.006)	(0.059)	(0.114)	(0.416)	(0.106)	(0.395)
RE_share	2.908**	3.267	3.144**	3.645*	2.943**	3.059*	2.585*	2.561	2.597*	2.523	3.016**	3.504	3.073**	3.593
	(0.042)	(0.132)	(0.025)	(0.088)	(0.034)	(0.079)	(0.073)	(0.152)	(0.068)	(0.153)	(0.040)	(0.122)	(0.035)	(0.113)
Experience	1.029*	1.603	1.050*	1.660*	1.139*	1.288*	1.178*	1.326*	1.366**	1.567**	1.240**	2.190**	1.118*	2.006**
	(0.093)	(0.103)	(0.083)	(0.090)	(0.053)	(0.082)	(0.052)	(0.087)	(0.024)	(0.042)	(0.043)	(0.026)	(0.067)	(0.040)
Consistency1_PS											−0.325	−1.226	−0.250	−1.109
											(0.775)	(0.472)	(0.825)	(0.515)
Consistency2_IM											−0.064	1.526	−0.262	1.128
											(0.963)	(0.473)	(0.854)	(0.604)
Consistency3_PM					4.158*	8.170***					1.144	3.284	4.044	8.511*
					(0.092)	(0.010)					(0.405)	(0.121)	(0.156)	(0.055)
Credibility_national			2.384	4.038	3.976	6.646*					1.958	1.591	4.193	5.661
			(0.135)	(0.111)	(0.149)	(0.059)					(0.395)	(0.651)	(0.205)	(0.279)
Credibility_subnational	2.336*	3.528*	1.810	2.671							1.475	1.686	1.266	1.314
	(0.067)	(0.079)	(0.164)	(0.194)							(0.271)	(0.422)	(0.352)	(0.537)
Cons3 X Cred_nat					−3.823	−7.786*							−4.405	−7.893
					(0.245)	(0.059)							(0.229)	(0.169)
Comprehensiveness							0.800	1.504			0.753	1.534	0.666	1.347
							(0.429)	(0.251)			(0.493)	(0.377)	(0.548)	(0.444)
Coherence_informational									0.517	0.967	−1.352	−1.008	−1.236	−0.805
									(0.760)	(0.651)	(0.507)	(0.745)	(0.539)	(0.794)
Coherence_procedural									1.920	2.575	1.863	2.522	2.125	3.092
									(0.247)	(0.224)	(0.342)	(0.402)	(0.278)	(0.308)
Constant	−15.346***	−25.850***	−16.737***	−28.331***	−16.734***	−22.737***	−14.061***	−18.288***	−15.294***	−19.652***	−18.244***	−30.992***	−19.374***	−33.239***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Log (Pseudo) likelihood (χ^2)	−847.931 (134.84)***		−846.337 (153.36)***		−916.058 (127.27)***		−925.087 (98.75)***		−913.242 (105.06)***		−801.416 (187.12)***		−800.111 (190.15)***	
Rho (χ^2)	0.958 (327.725)***		0.958 (325.793)***		0.925 (300.305)***		0.925 (307.375)***		0.924 (298.994)***		0.961 (315.651)***		0.961 (314.653)***	
AIC	1737.862		1738.674		1882.116		1892.174		1872.484		1672.831		1674.221	
BIC	1806.269		1813.596		1964.822		19,61,752		1948.460		1785.354		1793.174	
Observations	192		192		202		203		201		184		184	

Legend: PS = policy strategy, IM = instrument mix, PM = policy mix, Cons3 = third-level consistency, Cred_nat = credibility at national level, 4C = four policy mix characteristics; Robust p-values in parentheses; *** p < 0.01, ** p < 0.05, * p < 0.1.

6. Discussion

Keeping in mind the explorative character of our study we find evidence that in the case of renewable power generation technologies in Germany policy mix characteristics matter for innovation. In particular, by incorporating a distinct block of questions on companies' perceptions of the current policy mix our econometric analysis suggests a positive link between the *consistency* and *credibility* of the policy mix and corporate innovation expenditures on low-carbon innovation. In our case, this finding implies that technology providers that consider the instrument mix to be fairly well aligned with the expansion targets for renewable electricity and which perceive a high level of governmental commitment—at both the national and sub-national levels—spend more on low-carbon innovation. This relevance of policy mix consistency and credibility is in line with findings from qualitative research that have been reported in the literature. For example, as noted above, Uyarra et al. (2016) find that the UK policy environment with its various policy changes lacked consistency and strong signals about priorities, thereby hampering private investment and innovation activities in the UK.

We also find evidence that the innovation impact depends on the interplay between the consistency of the overall policy mix and policy mix credibility at the national level. More specifically, the effect of perceived policy mix credibility on innovation expenditures seems to be larger when perceived policy mix consistency is low. By the same token, the effect of perceived policy mix consistency on innovation expenditures was larger when credibility was perceived as low.

These findings may be reassuring to policymakers that are firmly committed to a low-carbon energy transition but who may not be able to align the entire policy mix with novel green targets at the same time. For example, conflicting policy objectives and political resistance from incumbents and others negatively affected by sustainability transitions are likely to slow the necessary changes. Indeed, the resulting inconsistencies may be partly unavoidable and inherent to such transitions (Quitzow, 2015a; Rogge and Reichardt, 2016), but the associated detrimental impact on green innovation may be reduced—at least in the short term—if innovators perceive a strong political commitment and thus high policy mix credibility. Similarly, the qualitative findings by Reichardt and Rogge (2016) show that policy makers were able to partly offset inconsistencies in the policy mix for offshore wind power in Germany by showcasing a high level of credibility, thereby reducing negative impacts on innovation.

In contrast, our study offers no support for earlier findings of a positive effect of instrument mix *comprehensiveness* on innovation (Costantini et al., 2017). This may be explained, for example, by differences in technologies (energy-efficient versus renewable technologies), indicators of innovation (patents versus innovation expenditures), estimation methodology (panel versus cross-section analysis), regional scope (OECD countries versus Germany) or data sources (secondary versus primary data). Perhaps comprehensiveness is more important for adoption decisions than for innovation decisions (Reichardt and Rogge, 2016; Sovacool, 2009).

Regarding the *coherence* of policy processes as the fourth policy mix characteristic included in our study, we do not find sufficient evidence for a direct link with innovation. It is noteworthy, however, that respondents were easily able to respond to our various items on the coherence of policymaking and implementation, and that, based on their answers, we arrived at two distinct factors capturing procedural and informational coherence. Also, the relatively low p-value for procedural coherence indicates that it may be worthwhile investigating this phenomenon further in a larger sample. This suggestion is supported by qualitative work which finds that policymaking style affects innovation in offshore wind power generation in Germany (Reichardt et al., 2017). Of course, an alternative explanation of our results may be the potential omission of key items needed to capture policy mix coherence. Finally, coherence might rather play its role in innovation more indirectly, for example by influencing the credibility of the policy mix (Rogge and Dütschke, 2018).

Turning to *technology push* instruments, we find that public financial support for innovation projects is linked with higher private innovation expenditures in the future.[29] This positive link is in line with the literature finding that public R&D support stimulates green innovation, albeit with some variation across technologies (Costantini et al., 2015; Johnstone et al., 2010). Yet, perhaps more importantly, our study adds to existing evidence suggesting that the locus of public technology push funding matters, but qualifies this for Europe where companies have access to both national and EU R&D funding, which matter jointly.[30]

Regarding *demand pull* effects our study supports earlier reported findings that market growth—which in the case of renewable energies at the time of our survey has still been mainly policy-induced—is positively associated with green innovation (Hoppmann et al., 2013; Horbach, 2008). In our case, technology providers who expect their green sales to increase compared with the previous year tend to spend more on low-carbon innovation. Of course, this growth expectation measured at the firm level rather than through national or global capacity additions depends not only on policy-induced market growth but also on the international competiveness of firms, where, for example, in the case of solar PV German companies have been particularly challenged by Chinese competitors (Quitzow, 2015b). Ultimately, global market expectations matter. In the case of green innovation expectations have been driven largely by policy mixes, with demand pull instruments as well as targets playing a key role (Johnstone et al., 2010; Rogge et al., 2011; Schmidt et al., 2012).

In terms of our *control variables* we find strong evidence that firm *size* (measured in total sales in 2013) and *financial resources* (measured in sales per employee) positively affects low-carbon innovation expenditures. These results are in line with others reported in the eco-innovation literature (del Río et al., 2016; Kammerer, 2009; Kesidou and Demirel, 2012). In addition, we also find evidence that *experience* with the main renewable power generation technology (measured in years) positively correlates with green innovation expenditures, suggesting that early movers spend more on green innovation. This also underlines the importance of green technological and organizational capabilities found in the eco-innovation literature (Demirel and Kesidou, 2011; Horbach et al., 2012; Kammerer, 2009). Regarding the *technology portfolio* our findings hint at possible differences across technologies (Huenteler et al., 2016), with companies active in on- and offshore wind power committing to higher innovation expenditures than the rest. Furthermore, firms with a higher share of employees working in the main renewable power generation technology were found to spend more on green innovation.

Overall, we argue that our explorative study provides empirical support for drawing on the broader policy mix concept introduced by Rogge and Reichardt (2016). In particular, we find strong evidence for a positive relationship between innovation expenditures in renewable power technologies and the overall consistency of the policy mix, i.e. how well aligned the instrument mix is with policy targets. Our findings also suggest that policy mix credibility plays a key role, although the mechanisms through which credibility—and its link with consistency—matters for innovation remain less than fully understood. Our findings further suggest that studies with a larger sample size can be expected to shed more light on the relevance of policy mix characteristics—and their interdependencies—for green innovation. Similarly, studies involving several countries could not only improve statistical power, but also exploit variation across countries to provide deeper insights into the links between policy mix characteristics and green innovation.

[29] One explanation could be that the positive impact of public R&D funding on future innovation expenditures might result in part from its often multi-annual nature, which might at least partly contribute to pushing future expenditure upwards.

[30] Findings are robust to using R&D funding from Germany only (rather than the combined funding from Germany and the EU used for creating *TechPush*).

7. Conclusion

In this paper we present new insights into the link between policy and innovation. More specifically, operationalizing policy mix consistency, credibility, comprehensiveness and coherence in an innovation survey enabled us to perform the first survey-based quantitative analysis of the relevance of these policy mix characteristics for green innovation. Our findings in the research case of manufacturers of renewable power generation technologies in Germany provide empirical support for the proposition that policy mix consistency and credibility matter for innovation. We also find evidence for mutual interdependencies between consistency and credibility. Moreover, our results fail to support some reported in earlier studies which had found the comprehensiveness of the instrument mix to be key for green innovation. Our findings also contribute to the innovation studies literature more broadly, confirming the relevance of paying greater attention to policy mixes (Cantner et al., 2016; Guerzoni and Raiteri, 2015) but suggesting a broader scope for future policy mix research.

Clearly, our novel empirical research is not free from limitations. Rather, it should be seen as a first step in analyzing the impact of policy mix characteristics on green innovation. First, for such an exploratory study choosing the German *Energiewende* makes it possible to draw lessons from one of the most advanced cases of a low-carbon transition. The focus on one country and one sector implies however that our results may not readily be transferable to other contexts. Second, while operationalizing policy mix characteristics proved feasible within an innovation survey, and the correlations found between innovation and the policy mix variables build upon and support earlier qualitative findings, we also recognize the caveats inherent to survey-based research such as recall bias, social desirability bias and common method bias. In addition, to establish causality, panel data would be preferable. Third, our operationalization of the measurement of perceptions of the policy mix should be seen only as a first attempt. For example, future studies could include strong instrument mix consistency characterized by the existence of synergies between instruments rather than just capturing the absence of contradictions, or could test multiple alternative items for comprehensiveness.

To move beyond our focus, future work could cover more than just energy and climate policy strategies by examining consistency between environmental and other policy objectives, such as industrial policy or distributional concerns. Similarly, based on our in-depth study of the German policy mix, future analysis should extend the scope, so as to include, for example, the Paris Climate Agreement or EU climate and renewable energy targets as such international long-term targets may also influence innovation strategies (Johnstone et al., 2010; Schleich et al., 2017; Schmidt et al., 2012). In light of the increasingly global nature of the market for renewable power generation technologies, studying the differential effects of domestic and global policy mix characteristics also seems promising.

Despite these caveats we argue that our findings not only bear relevant implications for German policymakers but also provide important indications for transformative innovation policy more generally (Schot and Steinmueller, 2016). First, our results suggest that policymakers interested in stimulating green innovation are well advised to think more holistically in terms of the consistency of the *overarching* policy mix, that is, striving for instrument mixes which are mutually supportive and well aligned with long-term targets. Second, since policy mix *credibility* seems to stimulate green innovation (at both the national and sub-national levels), policymakers need to recognize this relationship and better understand the formation (and loss) of such credibility. Finally, the decarbonization of the economy requires dedicated efforts to better monitor the greening of innovation and the drivers thereof. For example, standard monitoring tools, such as the CIS, should be adjusted to provide a better base for evidencing the role of policy mixes for the steering of such a transition to a green economy.

Based on the results of our exploratory study we foresee three main areas for future research, all intended to deepen empirical insights into the innovation impact of policy mixes for sustainability transitions. First, conducting a periodic innovation survey among manufacturers of technologies that are relevant to the low-carbon energy transition may help when investigating the causality of policy mixes and innovation. Such a *panel* should include not only technology providers that are active in the field of renewable energy, but also capture the ongoing system innovation more broadly, e.g. by also including complementary or enabling technologies, such as storage or grid technologies. Second, to better understand the relevance of the characteristics of policy mixes, such as consistency and credibility, *cross-country innovation surveys* should be conducted. For example, a comparative study of countries with a similar industry structure but alternative governance approaches regarding the transition of the energy system, such as the US, France, Japan and Italy, could enable important insights into the link between policy and low-carbon innovation.

Finally, analyzing the relevance of policy mixes for green innovation should be extended beyond the energy domain to capture its role in the greening of the economy more generally. For example, the CIS or similar surveys could include policy mix questions to allow for *cross-sectoral comparisons*. If implemented in more than one country, this would also allow for cross-country comparisons. Larger samples could also make possible a stronger consideration of further policy mix aspects, such as instrument interactions and the role of specific instrument design features for green innovation. In addition, larger samples would also enable the consideration of additional firm characteristics, including whether specific firm characteristics might be associated with a more profound policy impact on corporate green innovation.

Ultimately, we hope the findings of our explorative study will initiate a critical assessment of how policy and green innovation are measured in innovation surveys and beyond. Clearly, further research is needed to help establish new standards in innovation surveys, where items on policy are not limited to an optional eco-innovation module, but where both policy mixes and green innovation are integrated more holistically.

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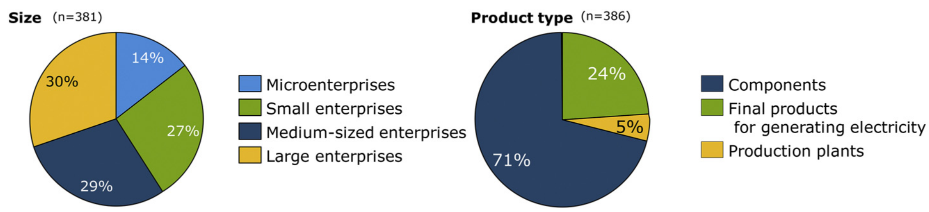
Appendix A



LEGEND (Size)	Microenterprises	Small enterprises	Medium-sized enterprises	Large enterprises
Turnover: Employees:	up to €2 million up to 9 persons	up to €10 million up to 49 persons	up to €50 million up to 249 persons	more than €50 million more than 249 persons

Fig. A1. Size and product type of participating companies.

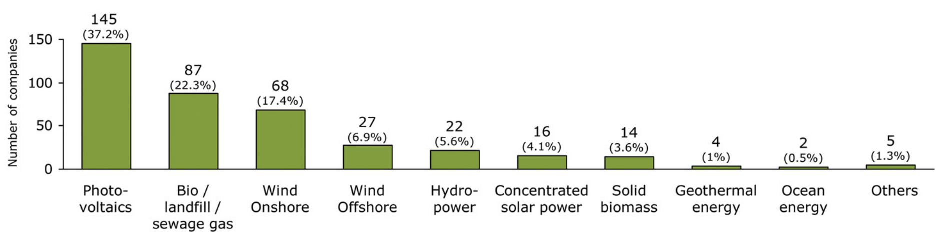


Fig. A2. Technologies for which the survey was completed (n = 390).

Appendix B.

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.respol.2018.05.011.

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