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Energy transition in Germany and regional spill-overs: The diffusion of renewable energy in firms☆

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ABSTRACT

The success of transitioning energy consumption towards renewables highly depends on the willingness and ability of firms to adopt energy technologies that use renewable sources. Existing studies focus on the role of regulation and energy markets to explaining the diffusion of green energy. This paper looks at the specific role of the firms' regional environment in this process. We use a unique database combining the Community Innovation Survey 2014 for Germany and district-level data on renewable energy plants, the attitudes of a region's population towards 'green issues' and other control variables. We find that geographical proximity to electricity production based on renewable energy sources and the orientation of a region towards 'green issues' are both correlated to such innovations. Therefore, not only "hard" regulation measures such as the renewable energy law are relevant for renewable energy innovations. Our results show that subsidies for eco-innovation, high energy costs and regional knowledge spill-overs are linked to a rapid adoption of renewable energy by firms.

1. Introduction

Shifting energy consumption from fossil sources to renewables is a key policy objective in many countries, including Germany. In 2016, Germany attained a share of 29% of renewable energy sources in gross electricity generation while fossil energy sources contributed 53.6% (hard coal 17.2%, lignite 23.1%, natural gas 12.4%, oil 0.9%) (BMWi, 2017a). Following the goals of the German federal government, the share of renewables shall rise up to 45% in 2025 (BMWi, 2017a). For 2050, a share of 80% is targeted. To reach these ambitious goals, innovations are required which substitute fossil energy sources by renewables.

At first glance, regulations such as the German renewable energy law seem to be one of the most important determinants to introduce renewable energy innovations (see Gawel et al., 2014; Frondel et al., 2010; Rammer et al., 2017; Stucki et al., 2018) but the importance of this nationwide law cannot explain the significant regional differences in renewable energy innovation activities. In the innovation literature, regional spill-overs (see Cantner et al., 2016) and tacit knowledge receive more and more attention as drivers for technology diffusion, whereas the growing literature on the determinants of eco-innovation widely neglects these effects. The present paper tries to assess the relevance of regional factors for innovation in renewable energy, which is an important subfield of eco-innovation. We use a unique database combining three data sources. The main source is the Community Innovation Survey (CIS) 2014 for Germany which contains detailed information on eco-innovation activities and their drivers at the firm level, including information on eco-innovations that substitute fossil by renewable energy sources in a firm's internal processes, and the role of environmental regulations or government subsidies for introducing these eco-innovations. This firm-level database is matched with regional data on renewable energy plants (solar, water, wind and biomass) as well as data on the attitudes of a region's population towards green issues at the geographical level of German districts ('*Kreise*' and '*kreisfreie Städte*'). The regional data enables the analysis of likely spill-over effects on the introduction of renewable energy innovations resulting from the green orientation of a region, or the regional endowment with a green energy capital stock. Our econometric models attempt to assess the importance of these effects while controlling for the relevance of environmental policy measures, energy costs and the technological capabilities of a firm.

The paper is organized as follows. Section 2 describes the theoretical framework of the relevance of regional spill-over effects on renewable energy innovations. Furthermore, the section contains an overview of

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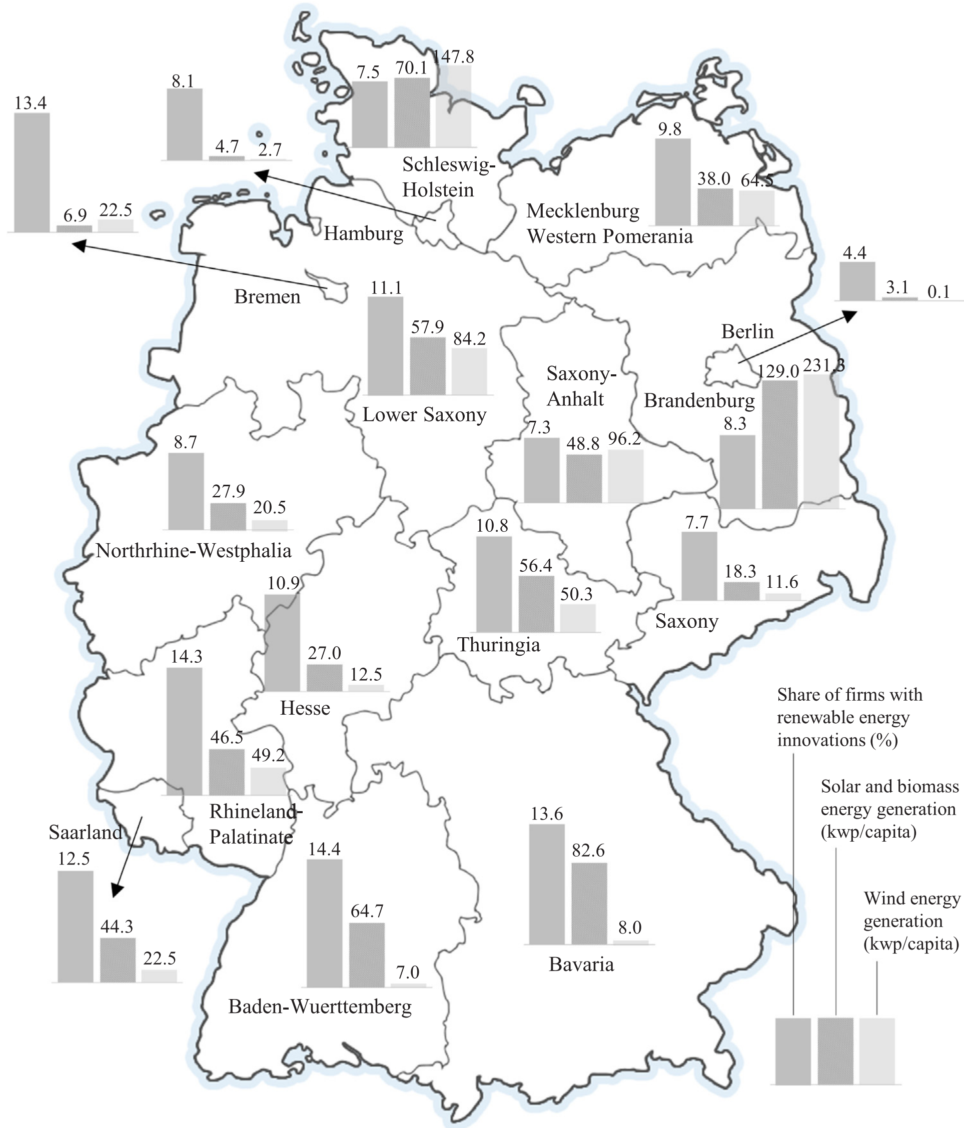

Fig. 1. Diffusion of renewable energy innovations in firms, and renewable energy generation per capita in German States 2014. Source: Statistisches Bundesamt (2017), German CIS 2014, own calculations.

empirical literature related to our research. Section 3 discusses the database, descriptive statistics and the econometric estimation strategy. Section 4 presents the estimation results. Section 5 concludes and develops policy recommendations.

2. Determinants of renewable energy innovations

In this paper, renewable energy innovations are defined as process innovations that lead to a substitution of fossil energy sources by renewable sources within firms. In most cases, this substitution is cost-intensive and will be undertaken by firms only if costs of fossil energy sources rise significantly, or if governments provide subsidies for renewable energy innovations (see Popp et al., 2010; Horbach et al., 2012). In addition, firms may be pushed to substitute fossil by renewable energy sources if regulation on emissions (e.g. CO_2) become more stringent. While these factors usually affect all firms with a similar energy consumption pattern in the same way, substantial regional differences in renewable energy innovation can be observed across the Federal States of Germany (see Fig. 1). States in the western part of Germany tend to show a higher diffusion of renewable energy technologies among firms, especially Rhineland-Palatinate, Baden-Wurttemberg and Bavaria. The two last-mentioned states also show a disproportionately high stock of solar and biomass plants per capita whereas the wind plants are more concentrated in the Northeast of Germany. North Rhine-Westphalia, Hesse, Hamburg and Berlin all report rather low shares of firms with renewable energy innovations and a low level of energy generation based on renewables. However, there are also states with a high level of renewable energy generation and a low innovation activity of firms in the field of renewable energy technologies like Brandenburg and Schleswig-Holstein.

The main aim of this paper is to explain the regional differences and to identify regional determinants of eco-innovations in the field of renewable energy. As the geographical level of states is too heterogeneous in terms of size and the regional situation for adopting renewable energy technologies, the analysis is conducted at the much more disaggregated level of districts, covering almost 400 geographical units.

While the literature on the determinants of eco-innovation is growing fast (see e.g. Barbieri et al., 2016 for a recent overview), the inclusion of regional aspects still remains rare (see Antonioli et al., 2016; Cantner et al., 2016, Horbach, 2014 as exceptions). We argue that regional factors can play a prominent role in the diffusion of eco-innovations, particularly if a decentralized approach is followed. The decentralized approach is based on the conversion of energy from renewable sources into electricity or heat at the location of the energy users through small renewable energy facilities (photovoltaic cells, solar panels, biomass power plants, geothermal energy plants) or based on regional producer organizations (in the case of wind power) (Vona et al., 2012). In contrast, the centralized approach rests on firms from the energy sector who convert their production units from fossil to renewable energy sources and distribute electricity (or other forms of energy) based on renewables to their customers. Germany mainly followed the decentralized way. In this approach, adopting renewable energy technologies by energy consuming firms is a major driver for energy transition.

The diffusion of renewable energy technologies - as the diffusion of other technologies - can be facilitated (or impeded) by a number of factors, including the information available to potential adopters on the cost and feasibility of new technologies, and the technologies' market prospects. In the pioneering work of Rogers (1962) on the diffusion of innovation, the interaction of actors and the existence of a critical mass have been identified as key factors. Communication reduces information asymmetries among potential adopters and provides potential adopters more realistic information about costs and expected returns. A critical mass reduces the cost of adoption by allowing technology providers to leverage economies of scale and specialize on specific user requirements. We argue that both processes are critical for the adoption of renewable energy technologies by firms, and that spill-overs within a region can be an important driver for the decision of firms to adopt renewable energy technologies.

A first mechanism refers to awareness and learning. As renewable energy technologies are not essential for firms' operations, firms do not regularly monitor the market for these technologies and have little information about expected returns of such an investment. The presence of other adopters in their regional environment can provide a kind of demonstration effect (Beise and Rennings, 2005; Bossink, 2017). Regional actors that have successfully implemented renewable energy technologies are 'role models' to other firms which are encouraged to follow. Exchange with these nearby actors will reduce information asymmetries and demonstrate the potential gains from adopting renewable energy technologies. Especially the diffusion of organizational innovations such as the re-organization of production units can strongly profit from mutual learning and the exchange of experience within regions since the codification of the critical knowledge e.g. through patenting and the trade of these innovations through embodied technology is restricted. This argument is in line with Antonioli et al. (2016:5) who stress that "the degree of closeness to other firms that adopt EIs [environmental innovations] and the presence of homogeneous institutional conditions in a given territory can influence the diffusion of EIs through knowledge transfer."

A second mechanism is related to reputation. For almost all firms, adopting renewable energy technologies at their own premises is neither part of their core business nor does it significantly affect the competitiveness of their business activities. For consumers, it was shown that concerns about the negative consequences of maintaining a carbon-based energy model stimulates the adoption of green energy (Band et al., 2000). Though firms are usually less driven by environmental concerns, a regional population that is highly concerned about environmental problems can incentivize firms to adopt green energy. First, positive reputation effects that can enhance a firm's marketing efforts (see Dangelico and Pujari, 2010). Secondly, reputation building can also improve a firm's operations e.g. when it comes to enlarging production activities or attracting skilled workforce.

A third mechanism is linked to the costs of adopting renewable energy technologies. The lower these costs, the more firms will adopt such technologies (see Neij, 1997 on the case of renewables). At the same time, an increased number of adopters will lower technology costs since technology suppliers can utilize economies of scale and can specialize on the specific requirements of potential users. In the case of renewable energy, potential adopters do not only demand the renewable energy components (such as solar panels) but also specialized services to install these technologies and, more importantly, integrate them into the firm's existing energy supply and production systems. A pre-condition is that the firms are ready and able to change business processes or customer and supplier relationships. Note that renewable energy innovations can also include a change in a firm's energy process, e.g. replacing fuel-based by electricity-based processes. In this context, localization economies can play an important role as the presence of many firms from the same sector in one region allows for the emergence of specialized service providers which lower the costs of adoption.

Besides localization advantages, positive agglomeration effects might also result from the so-called urbanization advantages. These advantages result from the existence of a high number of firms from different industries and from the typical advantages of highly concentrated urban areas (e.g. more leisure and cultural opportunities and a higher product diversity) (Eckey, 2008).

Regional factors are not the only determinants for renewable energy innovation. The literature has been stressing the role of regulation and government subsidies which operate as a push/pull mechanism in driving eco-innovation (e.g. Horbach et al., 2012; Demirel and Kesidou, 2011). Germany has followed this approach with the Renewable Energy Sources Act (EEG). This law aims "…to increase the proportion of electricity generated from renewable energy sources as a percentage of gross electricity consumption to 1) 40 to 45 percent by 2025, 2) 55 to 60 percent by 2035 and 3) at least 80 percent by 2050" (BMWi, 2017b:1). Fixed feed-in tariffs and purchase guarantees support the introduction of renewable energies by lowering the relative energy prices in favor of renewables so that their proportion of gross power consumption increased from 6% in 2000 to 31.7% in 2016 (BMWi, 2017a). In addition, there are several regulations in Germany that aim at reducing CO_2 and other emissions resulting from production processes (Blesl et al., 2007) which stimulate firms to substitute fossil energy by renewables.

Another factor for adopting renewable energy technologies are energy costs. Higher energy prices often accompany the adoption of more energy efficient technologies or a shift towards energy technologies that avoid energy sources which become more expensive over time (Linn, 2008; Persson et al., 2007; Ley et al., 2016). Increasing energy prices for fossil sources and particularly the expectations of firms of rising prices in the future are an important push factor for adopting green energy technologies that consume less or no fossil energy (Wörter et al., 2017; Arvanitis et al., 2017). Besides these cost-related factors, firm-internal factors such as the capability for organizational changes and the social responsibility of a firm might be relevant for the willingness to adopt renewable energy technologies (Horbach and Jacob, 2018).

Based on the arguments presented above, we derive a number of hypotheses. We expect a firm's propensity to adopt renewable energy technologies to be higher:

H1. the higher the diffusion of renewable energy technologies in the region is (learning and awareness effect);

H2. the stronger a region's orientation towards 'green issues' is (reputation effect);

H3. the higher the share of a firm's industry in total regional activities is (localization effect);

H4. the higher government support for renewables through regulation or subsidies is (policy push/pull effect);

H5. the higher the expected increases in energy costs are (resource push effect);

H6. the higher the change management capacities and the social responsibility of the firm are.

While policy push/pull effects and resource push effects can drive renewable energy innovations, they may also incentivize other types of eco-innovation, e.g. increasing energy efficiency of production processes or investing in technologies to reduce emissions. Whether these effects are stronger for renewable energy innovations or other eco-innovations will depend on a number of firm-specific factors, including the production technology used and the types of products produced. In the empirical part, we will examine the relative importance of policy push/pull effects and resource push effects for renewable energy innovations as compared to other eco-innovations. For the first three hypotheses (learning/awareness, reputation and localization effects) and hypotheses 5 and 6, we expect that they will be stronger related to renewable energy innovations as compared to other eco-innovations because these effects are specific to renewables.

The determinants of eco-innovation have been extensively analyzed (see also Barbieri et al., 2016 or Horbach, 2015 as overviews). In the following, we concentrate on the results of recent studies that empirically investigated the introduction and diffusion of renewable energy innovations as a special field of eco-innovation. We first examine studies that analyze the introduction of renewable energy technologies in general and then focus on studies that look on specific technologies (wind, solar).

Nesta et al. (2014) analyze the determinants of renewable energy innovation, considering policy-inducement mechanisms, market structure, demand, social cohesion, and a country's knowledge base. Renewable energy innovations are identified through patent data for OECD countries, covering the period 1970–2005. They find a significantly negative influence of entry barriers and inequality on renewable energy innovation whereas product market liberalization triggers green patent generation, especially in combination with ambitious energy policies. Their patent analysis also accounts for the endogeneity of environmental policy. Using data on patent applications from the EU15, the US and Japan Conti et al. (2016) estimate the relevance of knowledge spill-overs among economic actors within a region for renewable energy innovators from 1985 to 2010. The authors show that "…knowledge flows within the EU15 are weaker than in the US and Japan, and knowledge flows within a EU15 member country are higher than between members" (Conti et al., 2016:11). Noailly and Smeets (2016:5) analyze the role of financial constraints for the realization of renewable energy innovations. They find that innovative newcomers in the field of renewable energy are especially concerned by financial constraints "…not solely because they are younger and less mature than other established firms, but mainly because they focus on new clean technologies that are still perceived as more risky by investors than the incumbent technologies based on fossil-fuel electricity generation." Furthermore, Foster et al. (2017) point out that the cost of fossil fuel power generation will respond to the increased use of renewables thus leading to a delay of the diffusion of renewables.

Several papers considered the role of energy policy for the adoption of renewables. Johnstone et al. (2010) analyze the effects of different policy instruments on the development of renewable energy technologies. Their patent analysis reveals a high importance of feed-in-tariffs for solar energy whereas more cost-competitive technologies such as wind power are not triggered by this policy instrument. Groba and Breitschopf (2013) confirm the crucial role of specific renewable energy policies to overcome market failures and barriers for the introduction of renewable energies.

Wörter et al. (2017) employ a large sample of firms from Austria, Germany and Switzerland. They find that policies promote the decision to adopt green energy technologies but they are ineffective in driving the size of the investment. The paper also clarifies that the effectiveness of various policies differs across countries. Subsidies turned out to be more effective in Austria, taxes were more effective in Germany, and demand-related factors were more effective in Switzerland. In a related paper based on the same data, Stucki et al. (2018) analyze the effects of regulation measures, energy taxes, voluntary agreements and subsidies on the development of green energy product innovations. If taxes and regulations do not support additional demand, their influence is negative with respect to energy product innovations whereas subsidies and voluntary agreements are positively correlated to energy product innovations.

Among the studies looking at specific renewable energy technologies, Pohl and Mulder (2013) find a positive role of regulatory instruments, higher per capita income and schooling levels as well as stable, democratic regimes for the diffusion of non-hydro related renewable energies in 108 developing countries between 1980 and 2010. In a recent analysis, Schleich et al. (2017) explore the determinants of wind power technologies in twelve OECD countries using patent counts. The stock of wind capacity, a country´s innovative capacity (measured by the number of patents per capita) and the legitimacy of wind technologies (measured by the share of green party voters) supports innovations in wind power technologies. Furthermore, a stable policy environment is conducive. Cantner et al. (2016) also use patent data to evaluate the influence of different policy instruments on technological change and efficiency gains in wind power and photovoltaics. The authors find significant differences between the driving forces of these renewable energy technologies. Whereas wind power is mostly driven by technology push instruments, demand pull seems to be more relevant for photovoltaics. The patent analysis of Corsatea (2016) for 20 Italian regions shows that a localized stock of knowledge, public research subsidies and the regional endowment with hydroelectric resources trigger renewable innovation activities. Costantini et al. (2017) stress the point that a well-balanced policy mix of demand-pull and technology-push instruments is crucial for innovation in energy efficiency technologies.

All in all, the existing studies widely neglect the relevance of regional variables for renewable energy innovations (Corsatea, 2016; Cantner et al., 2016 as exceptions). Using a unique combination of three databases (see Section 3), the present study aims at filling this research gap. The paper can be understood as a first step to enlarge the analysis of the diffusion of renewable energy innovations by including regional spill-over effects between firms whereas most of the existing literature concentrated on the analysis of "hard" policy measures. Unfortunately, the data possibilities for such analyses are still restricted. For future analyses, panel data allowing more causality-oriented analyses would be necessary.

3. Data and estimation strategy

3.1. Data

Our study is based on a unique data set which combines firm-level data from the German part of the Community Innovation Survey (CIS) of the reference year 2014 and regional data at the level of German districts (*'Kreise'* and *'kreisfreie Städte'*) on installed renewable energy capacities and other regional factors such as the attitudes of the population towards green issues. The German CIS 2014 contains data from 8684 firms in mining, manufacturing, energy and water supply, and a large number of service sectors (wholesale, transport, information and communication, financial services, professional, scientific, technical, administrative and support services). The survey follows all the methodological recommendations of Eurostat for conducting the CIS, including stratified random sampling, several reminders and a non-response analysis (see Peters and Rammer, 2013 and Behrens et al., 2017 for details). The response rate of the German CIS 2014 was 25%, which is in line with comparable non-mandatory surveys.

The regional data are taken from three sources. Data on population density (in 2012), the regional industry structure (in 2012) and voting shares of the green party (in 2013) are provided by the regional database of the Federal Statistical Office in Germany (Statistisches Bundesamt, 2017). For regional data on renewable energy plants, we employ a database of the German Society for Solar Energy (DGS, 2018). This organization collects data on all plants that are regulated by the Federal Law on Renewable Energy (EEG). Plant operators are required by law to disclose certain data which feed the DGS database. The database includes the exact location (ZIP code), the type of the plant (solar, wind, water, biomass, gas, geothermal, biomass) and the installed capacity (kW h). Based on ZIP code information, we aggregate the data at the district level. The data refers to the installed capacity in 2013 and include both plants operated by firms and by private households (the latter being very common for solar energy). Furthermore, we use regionalized solar radiation data of the German Meteorological Office (DWD, 2018).

3.2. Variables and descriptive results

The CIS 2014 contained a separate module on eco-innovations, including information on the introduction of renewable energy technologies. Appendix A shows the individual questions of this module as used in the German version of the CIS 2014. An eco-innovation has been defined as follows: "An environmental innovation is a new or significantly improved product (good or service), process, organizational method or marketing method that creates environmental benefits compared to alternatives. The environmental benefits can be the primary objective of the innovation or the result of other innovation objectives. The environmental benefits of an innovation can occur during the production of a good or service, or during the after sales use of a good or service by the end user". The definition was followed by two questions on innovations that generated environmental benefits either within the firm or through the use of products or services. The first question on within-the-firm benefits contained nine items (see Table 1). Firms that reported to have introduced an eco-innovation that "replaced fossil energy sources by renewable energy sources" are the firms we will focus on. These innovations refer to changes in the firms' processes, e.g. by installing additional electricity generation capacities based on solar, biomass or water power, or by altering energy supply in production processes from fossil sources (oil, gas, coal) to electricity (and sourcing electricity from suppliers that generate electricity using renewables). In 2012–2014, 10.5% of all firms in Germany introduced renewable energy technologies.

In the CIS 2014, firms were also asked whether any of their eco-innovations have been introduced in response to eight factors. Table 2 shows these factors. Though the factors have not been asked separately for each type of eco-innovation, they still can be used to identify likely drivers for renewable energy innovations. For all firms reporting renewable energy innovations, present regulations (45.7%) and rising energy costs (61.6%) are most often named as highly or medium important drivers for the decision to introduce eco-innovations (Table 2). We use this information to identify the role of existing or expected regulations (including taxation), the role of government subsidies and the role of rising energy cost for a firm's decision to adopt renewable energy technologies.

A definition of all model variables along with descriptive statistics is provided in Appendix B. Our dependent variable *Renewable* takes the value one if the firm has realized an innovation that led to a substitution of fossil energy sources by renewables.

Popdens represents the population density of a region in the year 2012 and accounts for agglomeration effects (see Section 2). The variable *Sharegreen* represents the voting share of the green party in 2013. This variable serves as a proxy for green attitudes (ecological awareness) of the people living in a region and describes the social acceptance of green issues by relevant stakeholders (Horbach, 2014; Schleich et al., 2017). *Solbiocapita* captures the installed capacity of solar and biomass energy plants in kwp per capita for each district. As this variable also includes the solar plants of households *Solbiocapita* can also be interpreted as a revealed preference indicator for the green orientation of the regional population. *Watercapita* and *Windcapita* are the respective variables for water and wind energy plants. These variables capture the already available regional capital stock of renewable energy plants.[1] *Solintens* measures the annual sum of solar radiation at the location of each firm. This variable is relevant because it determines the cash flow of solar energy plants. Solar radiation data are provided by the German Meteorological Office at the level of more than 500,000 grid cells. Grid cell data were aggregated to postal areas and merged with firm-level data based on the firms' ZIP codes.[2] *Secshare* represents the share of the sector to which the firm belongs in a district's total employment in order to capture localization effects.

We include a number of other firm-specific variables that may be linked to a firm's decision to introduce eco-innovations (see Costa-Campi et al., 2015; Horbach et al., 2012; Wörter et al., 2017). The technological capabilities of a firm determine the in-house capabilities to develop and implement new technologies. They are captured by the

Table 1
Introduction of process-related eco-innovations in firms from Germany, 2012–2014. Source: German Community Innovation Survey 2014, own calculations.

Type of process-related eco-innovation	Share in all firms (%)
Reduced energy use per unit of output	32.2
Reduced material use / use of water per unit of output	21.6
Reduced CO_2 ‚footprint' (total CO_2 production)	18.5
Reduced air pollution (i.e. SO_x, NO_x)	11.8
Reduced water or soil pollution	10.6
Reduced noise pollution	14.1
Replaced fossil energy sources by renewable energy sources	10.5
Replaced materials by less hazardous substitutes	11.9
Recycled waste, water, or materials for own use or sale	19.1

Table 2
Factors driving firm decisions to introduce eco-innovations for firms that introduced renewable energy technologies. Source: German Community Innovation Survey 2014, own calculations.

Factors	Share in all firms with renewable energy innovations (%)[a]
Increasing cost of energy, water or materials	61.6
Existing environmental regulations	45.7
Improving the enterprise's reputation	45.2
Voluntary actions or standards for environmental good practice	40.7
Environmental regulations or taxes expected in the future	40.7
Existing environmental taxes, charges or fees	26.1
Current or expected market demand for environmental innovations	30.9
Government grants, subsidies etc. for environmental innovations	22.7

[a] Firms rating a factor as highly or medium important.

[1] Please note that the variables *Solbiocapita, Watercapita* and *Windcapita* also reflect the natural endowment of a region with solar radiation or wind speed because these renewable energy installations are only useful if there is enough solar, wind or water.

[2] We thank Philipp Massier and Jan Kinne for sharing this data.

following variables: *Internrd* gets the value 1 if the firm realizes internal R&D activities, *Externrd* describes external R&D activities. *Highqual* denotes the share of employees with a university degree. *Coopown* gets the value one if the firm cooperates within the own firm group. The variable *Org* describes organizational innovations including new methods organizing business processes, new methods organizing labor, or changes of the organization of external relationships to other firms, e.g. the integration of suppliers thus indicating the change management capacities of the firm.

Profit represents the financial situation of the firm (measured by the profit margin). Firms with a profit margin of 2% or more are considered to be in a comfortable financial situation. The competitive environment of a firm is represented by two indicators. The variable *International* equals one if a firm sells products in markets outside Germany. The second variable, *Competition,* captures the competition pressure a firm experiences from competitors abroad. Furthermore, sector dummies are included. Three variables capture structural characteristics of the firm. The variable *Size* measures the number of employees, and *Agefirm* represents the age of the firm in years. The variable *Family* gets the value one if the firm is dominated by one family (at least more than a 50% share). It is assumed that family-dominated firms show a higher regional social responsibility compared with internationally operating stock-listed companies.

The variables on the policy determinants of eco-innovation are only available for firms with eco-innovations. They get the value 1 if a determinant is rated as highly or medium important, and 0 otherwise and include *Regulation* (present regulations), *Taxes* (environmental taxes), *Futurelaw* (future regulations), *Ecosubsidies* (public subsidies of eco-innovations). In addition, *Demand* (present or anticipated demand), *Reputation* (improvement of the reputation of the firm) and *Selfcommitment* cover further factors that may be correlated to innovations in renewable energy. *Energcost* denotes rising costs of energy or other raw materials as determinant for eco-innovations.

3.3. Estimation strategy

In a first step, we estimate the probability of introducing renewable innovations for all firms in the sample. In a second step, we restrict our sample to eco-innovators only. The second step aims at analyzing the specificities of renewable energy innovations compared to other types of eco-innovation specifically with respect to the role of regulation and energy prices as drivers for the adoption of renewable energy technologies.

In all models, regional variables at the district level are matched to the firm-level data of the CIS leading to possible intra-cluster correlation so that the standard errors using normal probit models would be too low. We use multilevel mixed effects probit models to account for this problem and probit models with clustered standard errors as robustness checks. As cluster size in our sample varies significantly (from 1 to 725 firms) we perform multilevel mixed effects models. These models are more adequate compared to simple models with clustered standard errors.

Our two-level mixed-effects probit regression contains both random and fixed effects. The model reads as follows (STATACorp, 2015): We have to consider a two-level model for a series of 396 independent clusters (396 regional German districts)

$$Pr(y_{ij} = 1|\mathbf{x}_{ij}, \mathbf{u}_j) = H(\mathbf{x}_{ij}\boldsymbol{\beta} + \mathbf{z}_{ij}\mathbf{u}_j)$$

for j = 1; …; 396 clusters, with cluster j consisting of i = 1; …; n_j observations. The responses y_{ij} are the binary-valued renewable$_{ij}$. The vector $\mathbf{x}_{ij}$ are the covariates for the fixed effects, analogous to the covariates of a standard probit regression model with regression coefficients whereas the vector $\mathbf{u}_j$ analogously represents the random effects. H(.) is the standard normal cumulative distribution function. The vector $\mathbf{z}_{ij}$ contains the covariates related to the random effects. As we apply a random intercept model, $\mathbf{z}_{ij}$ is simply the scalar 1. The basis of this model is the variance components model (stated as latent linear response): $y_{ij}^* = \mathbf{x}_{ij}ß + \mathbf{z}_{ij}\mathbf{u}_j + \boldsymbol{\varepsilon}_{ij}$, where the errors $\boldsymbol{\varepsilon}_{ij}$ are distributed as normal and are independent of the random effects $\mathbf{u}_j$. The log likelihood function is approximated by Gauss-Hermite quadrature (STATACorp, 2015; Cameron and Trivedi, 2009).

4. Estimation results

4.1. Firms with renewable energy innovations compared to all firms

The results of both the two-level mixed effects models and the probit model with clustered standard errors (see Table 3) show significant effects of regional variables. A green orientation of a region (*Sharegreen*) is correlated to the willingness of firms to implement renewable energy technologies supporting our hypothesis H2 and the recent analysis of Schleich et al. (2017). The share of green party voters may be interpreted as "…social acceptance of renewable energy technologies" (Schleich et al., 2017:688). Furthermore, a high share of solar and biomass (*Solbiocapita*) in the region is connected with a higher substitution of fossil energy within firms pointing to considerable regional spill-over effects (Conti et al., 2016) supporting H1 whereas *Solintens* as indicator for the solar radiation at the location of each firm remains insignificant (see Model 2 in Table 3). Furthermore, the significant result for *Solbiocapita* supports H2 because this variable also captures the solar plants of households as indicator for the green orientation of a region. The firms seem to use existing regional experiences by learning from other firms (see Section 2) and capacities in renewables for their own substitution process of fossil fuels. This result does not hold for water and wind power plants as these power plants are highly dependent on geographical conditions. Agglomeration in the sense of urbanization effects do not seem to be a pre-condition for renewable energy innovations within firms, the indicator population density (*Popdens*) is even significantly negative whereas localization effects measured by a high presence of similar firms in the region are significantly relevant for renewables (*Secshare*) supporting H3. We also estimated models where we controlled for the energy intensity of the firm but, interestingly, the respective variable always remained insignificant. This may be due to the fact that energy intensive firms especially those having own power plants would have to realize high investment costs to change their energy mix. As the variable *Energy intensity* causes a drastic reduction of observations, we renounced including this insignificant variable.

The substitution process from fossils to renewables is highly correlated to organizational innovations within a firm. The introduction of new methods organizing business processes, new forms of labor organization, new cooperation arrangements, the change of customer relationships or a better integration of suppliers summarized by the variable *Org* indicates the change management capacities of a firm (H6) that are useful to realize renewable energy innovations. Larger and family-owned firms are more likely to introduce renewable energies (*Size, Family*). The positive size-effect may reflect the fact that larger organizations can easier bear the costs of the introduction of renewable energy innovations owing to their larger financial resources. Family dominated firms might have a higher preference to improve their reputation showing their social responsibility supporting H6.

Table 3
Determinants of the adoption of renewable energy technologies – all firms. Source: Community Innovation Survey 2014, own estimations.

Dependent variable: Renewable (substitution of fossil energy sources by renewables)			
Correlates	**Two-level mixed-effects probit regression**		**Probit model with clustered standard errors**
	Model 1	Model 2	
Regional variables			
Popdens	− 0.02 (−4.33)***	− 0.02 (−4.29)***	− 0.02 (−4.96)***
Secshare	0.10 (2.22)**	0.10 (2.22)**	0.10 (2.35)**
Sharegreen	0.49 (3.43)***	0.51 (3.46)***	0.50 (3.59)***
Solbiocapita	0.16 (2.11)**	0.17 (2.08)**	0.15 (2.02)**
Solintens	–	− 0.00 (−0.37)	–
Watercapita	0.92 (1.32)	1.02 (1.37)	1.03 (1.57)
Windcapita	− 0.02 (−0.35)	− 0.02 (−0.43)	− 0.01 (−0.28)
(Technological) capabilities			
Externrd	0.02 (1.74)*	0.02 (1.73)*	0.02 (1.74)*
Internrd	0.04 (4.36)***	0.04 (4.35)***	0.04 (4.36)***
Org	0.08 (10.1)***	0.08 (10.1)***	0.08 (10.1)***
Highqual	− 0.01 (−0.69)	− 0.01 (−0.68)	− 0.01 (−0.74)
Further variables			
Agefirm	0.23 (2.57)***	0.22 (2.57)***	0.23 (2.64)***
Competition	0.03 (3.82)***	0.03 (3.82)***	0.03 (3.87)***
Family	0.02 (3.61)***	0.02 (3.61)***	0.02 (3.60)***
International	− 0.01 (−0.69)	− 0.01 (−0.69)	− 0.01 (−0.70)
Profit	0.03 (4.30)***	0.03 (4.30)***	0.03 (4.29)***
Size	0.004 (2.10)**	0.004 (2.10)**	0.004 (2.08)**
	No. obs.: 7202 No. groups: 396 Wald $\chi 2$ (38) = 558***	No. obs.: 7202 No. groups: 396 Wald $\chi 2$ (39) = 560***	No. obs.: 7202 Wald $\chi 2$ (38) = 844*** Pseudo R^2 = 0.11

Marginal effects, robust standard errors, z-statistics shown in parentheses. The marginal effects for the continuous independent variables were calculated at their means. Concerning dummy variables the values report changes in probability for discrete changes of the dummy variables from 0 to 1. *, ** and *** denote significance at the 10%, 5% and 1% level, respectively. Sector dummies are included but not reported. Likelihood Ratio test of the two-level mixed effects model versus a simple probit model: Model 1: $\chi 2$ (1) = 4.31**, Model 2: $\chi 2$ (1) = 4.29**. As the results of the LR test are significant at the 5% level, the use of the two-level model has to be preferred over the simple probit model.

4.2. Specificities of renewables compared to other eco-innovations

In a second step, we restrict our analysis to eco-innovators which allows us to include variables on the relevance of different eco-innovation determinants in the model estimations (since these variables are only available for eco-innovators). This analysis helps to detect specificities of renewable energy innovations compared to other eco-innovation fields. The results show (Table 4) that present regulations and taxes (*Regulation, Taxes*) are less relevant for renewables compared to other eco-innovations whereas renewable energy innovations are more likely if firms expect new regulations or changes to regulations in the future (*Futurelaw*) (H4). The marginal effect (me) of 8% is higher compared to the other policy variables. Improving the *Reputation* of a firm is significantly more relevant (me 5%) for renewable energy innovations compared to other eco-innovations, confirming our expectation formulated in H2. Rising energy costs (*Energcost,* me 6%) seem to be a main motive to introduce renewables supporting H5. Firms in regions with an already high amount of solar energy and water-based plants (*Solbiocapita, Watercapita*) are more likely to substitute fossil energy by renewables also supporting H1. The green orientation (*Sharegreen*) of a region is more relevant for renewable energy innovations compared to other eco-innovation fields (H2).

The result that *Family* owned firms are more likely to realize renewable energy innovations is also confirmed when only eco-innovators are considered. A higher *Competition* pressure is positively correlated to renewable energy innovations. Bigger (*Size*) firms are also more likely to introduce renewables. These firms seem to have fewer constraints to finance the switch from fossil energy to renewables. Furthermore, this switch is only successful when the firms are capable and active in the introduction of new methods of business processes. The significant marginal effect of the variable *Org* indicates that the change management capacities of a firm allowing a re-organization of the whole production process is especially relevant for renewables compared to other eco-innovations supporting H 6. This argumentation is confirmed by the positively significant variable *Coopown* denoting the relevance of cooperation partners from the own firm group.

5. Conclusions and policy implications

The ongoing energy transition in Germany aims at substituting the majority of fossil energy sources by renewables for the production of electricity. The existing literature stresses the role of regulation activities and an adequate policy mix of technology push and demand pull measures as main drivers of the diffusion of renewable energy. Despite the fact that most of the relevant political measures in Germany such as the renewable energy law are nation-wide, the distribution of renewable energy innovation activities varies considerably among regions. The present paper tries to identify some factors that are linked to these regional disparities. Our econometric analysis is based on a unique combination of different databases: The main source is firm level data

Table 4
Determinants of the adoption of renewable energy technologies – eco-innovators only. Source: Community Innovation Survey 2014, own estimations.

Dependent variable: Renewable (substitution of fossil energy sources by renewables)		
Correlates	**Two-level mixed-effects probit regression**	**Probit model with clustered standard errors**
Regional variables		
Popdens	− 0.04 (−4.89)***	− 0.04 (−5.20)***
Secshare	0.16 (2.15)**	0.17 (2.22)**
Sharegreen	0.75 (3.22)***	0.76 (3.28)***
Solbiocapita	0.19 (1.86)*	0.19 (1.84)*
Watercapita	2.05 (1.84)*	2.11 (1.94)**
Windcapita	0.04 (0.42)	0.04 (0.44)
(Technological) capabilities		
Externrd	− 0.01 (−0.83)	− 0.02 (−0.84)
Internrd	0.01 (0.53)	0.01 (0.52)
Org	0.05 (4.07)***	0.05 (4.06)***
Coopown	0.08 (2.88)***	0.08 (2.84)***
Highqual	0.02 (0.48)	0.02 (0.47)
Determinants		
Regulation	− 0.04 (−2.33)**	− 0.04 (−2.34)**
Taxes	− 0.03 (−1.63)*	− 0.03 (−1.65)*
Futurelaw	0.08 (4.26)***	0.08 (4.29)***
Ecosubsidies	0.03 (1.60)	0.03 (1.58)
Demand	0.03 (1.29)	0.03 (1.30)
Reputation	0.05 (2.50)***	0.05 (2.53)***
Selfcommitment	0.03 (2.05)**	0.03 (2.06)**
Energcost	0.07 (4.84)***	0.07 (4.85)***
Control variables		
Agefirm	0.11 (0.76)	0.11 (0.79)
Competition	0.03 (2.62)***	0.03 (2.64)***
Family	0.04 (3.91)***	0.04 (3.87)***
International	− 0.02 (−1.67)*	− 0.02 (−1.69)*
Profit	0.05 (4.28)***	0.05 (4.29)***
Size	0.03 (4.64)***	0.03 (4.64)***
	No. obs.: 4427, No. groups = 390 Wald $\chi2$ (47) = 709***	No. obs.: 4427, Wald $\chi2$ (47) = 894***, Pseudo R^2 = 0.12

Marginal effects, robust standard errors, z-statistics shown in parentheses. The marginal effects for the continuous independent variables were calculated at their means. Concerning dummy variables the values report changes in probability for discrete changes of the dummy variables from 0 to 1. *, ** and *** denote significance at the 10%, 5% and 1% level, respectively. Sector dummies and constants are included but not reported. Likelihood Ratio test of the two-level mixed effects model versus a simple probit model: $\chi2$ (1) = 0.91. The result of the LR test is not significant so that a simple probit model might also be used. Nevertheless, the results of the two-level model are reported because this one is more adequate when cluster sizes are quite different.

from the Community Innovation Survey (CIS) 2014 for Germany which contains information on eco-innovation activities, including innovations in renewable energy. This database has been merged with data on renewable energy plants (solar, biomass, gas, water and wind) in a firm's region and with data on green attitudes of the regional population, using the share of votes for the Green Party. Both regional variables are measured for the time prior to the period for which data on eco-innovation activities have been collected.

The results of our econometric analysis show that both the existing capacity for renewable energy production in a region based on solar and biomass, and the share of green voters are positively linked to subsequent renewable energy innovation in firms. Though the time structure of our data may suggest a causal link between the regional environment and a firm's innovations in renewables, we refrain from interpreting our results in such a way. Since we only have cross-section data on firm innovation, we cannot exclude that unobserved prior eco-innovations of firms influenced the existing capacity for renewable energy production in a region.

Having said that, our results point to spill-overs within a region that drive the diffusion of renewable energy innovations. There seems to be a demonstration and learning effect from existing regional capacities in renewables for firms that want to substitute fossil energy sources by renewable ones. In addition, firms that operate in a region with a high share of ecologically sensitive people tend to receive more impulses to engage in renewable energy innovations.

Restricting our analysis to eco-innovators helps to detect specificities of renewable energy innovations compared to other eco-innovation fields. The results show that present regulations and taxes are less relevant for renewables compared to other eco-innovations whereas the firms perceive a positive influence of expected future regulations on their renewable energy innovations. Improving the reputation of the firm is more relevant for renewable energy innovations compared to other eco-innovations. Rising energy costs seem to be a main motive to introduce renewables.

All in all, our analysis shows that there is a positive link between renewable energy innovations in firms on the one hand, and the prior presence of renewable energy production plants and the environmental awareness of a region's population on the other hand. Both regional factors can reinforce the diffusion of renewables in a region and hence strengthen a path dependency. For energy policy, our results suggest that in addition to "hard" regulation measures such as the renewable energy law and the European emission trading system, soft instruments may also play a role in accelerating the diffusion of renewable energy technologies. Though the link is not necessarily a causal one, strengthening soft policy instruments such as measures to encourage social and environmental responsibility of managers or environmental awareness of the population can reinforce renewable energy diffusion in firms.

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Appendix A

See Fig. A1.

13 Environmental Innovations

An **environmental innovation** is a new or significantly improved product (good or service), process, organisational method or marketing method that creates environmental benefits compared to alternatives. The environmental benefits can be the primary objective of the innovation or the result of other innovation objectives. The environmental benefits of an innovation can occur **during the production** of a good or service, or during the after sales use of a good or service by the **end user**.

13.1 During 2012 to 2014, did your enterprise introduce innovations that had any of the following environmental benefits within your enterprise, and if yes, was their contribution to environmental protection rather significant or insignificant?

Please mark an X in each line!	*Yes, significant*	*Yes, insignificant*	*No*
Reduced energy use per unit of output	☐1	☐2	☐3
Reduced material use / use of water per unit of output	☐1	☐2	☐3
Reduced CO_2 ‚footprint' (total CO_2 production)	☐1	☐2	☐3
Reduced air pollution (i.e. SO_x, NO_x)	☐1	☐2	☐3
Reduced water or soil pollution	☐1	☐2	☐3
Reduced noise pollution	☐1	☐2	☐3
Replaced fossil energy sources by renewable energy sources	☐1	☐2	☐3
Replaced materials by less hazardous substitutes	☐1	☐2	☐3
Recycled waste, water, or materials for own use or sale	☐1	☐2	☐3

13.2 During 2012 to 2014, did your enterprise introduce new products or services with the following environmental benefits through the use of these products/services, and if yes, what was their contribution to environmental protection?

Please mark an X in each line!	*Yes, significant*	*Yes, insignificant*	*No*
A. Reduced energy use	☐1	☐2	☐3
B. Reduced air, water, soil or noise pollution	☐1	☐2	☐3
C. Improved recycling of product after use	☐1	☐2	☐3
D. Extended product life through longer-lasting, more durable products	☐1	☐2	☐3

If you answered „**Yes**" in **A, B, C** or **D**: How high was the share of sales with new products or services that had a positive environmental impact (as a percentage of your enterprise's total sales) in 2014? .... ca. ☐ %

13.3 During 2012 to 2014, how important were the following factors in driving your enterprise's decisions to introduce environmental innovations?

Please mark an X in each line!	*Degree of **importance*** High	Medium	Low	*Not relevant*
A. **Existing** environmental regulations	☐1	☐2	☐3	☐4
B. **Existing** environmental taxes, charges or fees	☐1	☐2	☐3	☐4
C. Environmental regulations or taxes **expected** in the future	☐1	☐2	☐3	☐4
D. Government grants, subsidies etc. for environmental innovations	☐1	☐2	☐3	☐4
E. Current or expected market demand for environmental innovations	☐1	☐2	☐3	☐4
F. Improving your enterprise's reputation	☐1	☐2	☐3	☐4
G. Voluntary actions or standards for environmental good practice within your sector	☐1	☐2	☐3	☐4
H. Increasing cost of energy, water or materials	☐1	☐2	☐3	☐4

If you answered at least „**Low importance**" in **A, B, C** or **D**: Please name the respective laws, regulations, environmental taxes of public support programmes:

Fig. A1. Survey question on eco-innovation in the German CIS 2014. Source: Eurostat (2015).

Definition of variables and descriptive statistics

See Table B1.

Table B1
Definition of variables and descriptive statistics.

Name of variable	Description	Mean	SD
Renewable	1: Innovations leading to a replacement of fossil energy sources by renewables, 0: firms without such innovations	0.11	0.31
Regional variables (district-level)	District: *'Kreise'* and *'kreisfreie Städte'*, which corresponds to the NUTS 3 level of the EU's geographical classification system		
Popdens	Population 2012 per qm^2/1000	1.07	1.26
Secshare	Share of a firm's sector in total employment in the district in 2012	0.17	0.13
Sharegreen	Voting share of the green party in 2013	0.09	0.04
Solbiocapita	Solar-, biomass and gas energy plants in (kwp per capita)/1000	0.05	0.06
Solintens	Annual sum in kWh/m² (mean 2011-2013) of solar radiation at the location of each firm/m^2	1101.5	61.8
Watercapita	Water energy plants in (kwp per capita)/1000	0.002	0.004
Windcapita	Wind energy plants in (kwp per capita)/1000	0.04	0.09
(Technological) capabilities	*(1 yes, 0 no; except for Highqual)*		
Externrd	External R&D activities	0.11	0.31
Internrd	Internal R&D activities	0.35	0.48
Org	New methods of organizing external relationships, new methods for organizing business processes, new forms of labor organization	0.32	0.47
Coopown	Cooperation with firms of the own firm group	0.04	0.20
Highqual	Share of employees with university degree	0.22	0.28
Determinants	*(1 high or medium, 0 low or not relevant)*		
Regulation	Existing environmental regulations	0.27	0.45
Taxes	Existing environmental taxes	0.15	0.35
Futurelaw	Anticipation of future regulations or taxes	0.20	0.40
EcoSubsidies	Public support for eco-innovation	0.11	0.31
Demand	Demand for eco-innovation	0.14	0.35
Reputation	Improvement of the reputation of the firm	0.22	0.42
Selfcommitment	Self-commitments or industry standards	0.21	0.41
Energcost	Increasing energy or material costs	0.35	0.48
Control variables			
Agefirm	Age of the firm (2014 – year of foundation + 0.5)/1000	0.03	0.04
Competition	Strong competition by foreign firms (1 highly relevant, 0 other)	0.30	0.46
Family	Family dominated (at least 50% of firm shares) (1 yes, 0 no)	0.52	0.50
International	Exporting in international markets (1 yes, 0 no)	0.45	0.50
Profit	1: profit margin 2% or more, 0 otherwise	0.44	0.50
Size	Number of employees 2012 (in 1000)	0.69	4.24
Sector dummies	*(1 yes, 0 no)*		
Sec1	Food products and beverages, tobacco	0.04	0.20
Sec2	Textiles, clothing, leather products	0.03	0.16
Sec3	Wood and paper products, printing	0.02	0.16
Sec4	Chemical and pharmaceutical industry	0.03	0.17
Sec5	Rubber and plastic products	0.02	0.15
Sec6	Glass, ceramics and concrete products	0.02	0.14
Sec7	Basic metals and fabricated metals	0.07	0.25
Sec8	Electrical machinery, electronics, instruments	0.05	0.22
Sec9	Machinery	0.07	0.25
Sec10	Motor vehicles, other transport equipment	0.02	0.16
Sec11	Medial products, furniture and other products	0.05	0.23
Sec12	Energy and water supply, mining, mineral industry	0.04	0.18
Sec13	Recycling, waste and waste water removal	0.04	0.20
Sec14	Wholesale trade	0.04	0.19
Sec15	Transport and logistics	0.07	0.26
Sec16	Media services	0.04	0.20
Sec17	Computer programming, data processing, telecommunication	0.04	0.21
Sec18	Financial intermediation	0.05	0.21
Sec19	Technical and R&D services	0.07	0.26
Sec20	Consulting and marketing	0.06	0.24
Sec21	Business services, other	0.11	0.32

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