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Effects of innovation stimuli regulation in the electricity sector: A quantitative study on European countries

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ABSTRACT

The energy transition is characterized by decarbonization, decentralization, and digitalization trends in the electricity sector, increasing the demand for novel technologies and innovation. Nevertheless, there are still challenges in the electricity sector to provide proper innovation incentives, often attributed to the slow technological dynamics of the sector and its regulated nature. As a response to insufficient levels of innovation, numerous European countries introduced innovation-stimuli regulations in the electricity sector during the second half of the 2000s. To evaluate the impact of these regulations on innovation, we employed a difference-in-differences (DiD) model on a panel data set with 21 European countries covering the period from 1991 to 2016, using patents as a dependent variable. In addition to the canonical DiD, we performed group-specific treatment effects to estimate the difference among the "early adopters" and "late adopters" countries of innovation-stimuli regulation. We find that the introduction of innovation-stimuli regulation has positively impacted patenting activities in the electricity sector, especially among the "early adopters". These results suggest that innovation-stimuli regulation can be an important regulatory tool to foster further innovation that is required to complete the energy transition.

1. Introduction

The energy transition requires substantial technology improvements from the power sector to ensure green and reliable electricity for a continuously growing world economy. However, studies highlight the limitation of market forces to provide the necessary incentives for investment in the development and diffusion of technologies that support more sustainability in the electricity sector (Popp, 2019). In this context, the literature reveals the necessity of specific regulations to foster innovation, especially in the electricity sector (Cambini et al., 2016b; Cambini et al., 2020; Blind, 2012).

These regulations are essential in the electricity sector due to its market structure, characterized by high levels of vertical integration, network externalities, and market failures. These characteristics determine the presence of regulatory authorities responsible for establishing the electricity firms' competition conditions, profit level, and service quality (Polemis and Tselekounis, 2021). Consequently, the sector's business activity is shaped by regulatory requirements to a larger degree than in other sectors (Baldwin et al., 2012).

Besides the mentioned existing regulations in place, a new type of regulation focusing on directing electricity companies' expenditure on research, development (R&D), and innovation have gained prominence across different countries, especially in Europe (Cambini et al., 2016a; EURELECTRIC, 2016; Haffner et al., 2019; Cambini et al., 2020). This initiative was motivated by the acknowledged slowdown in innovation rates and intended to change the sector's technological dynamic characterized by elevated investment costs, which are highly specific, long maturing, and dependent on suppliers, particularly the equipment manufacturers (Pavitt, 1984; Miozzo and Soete, 2001).

These new regulations have been called "innovation-stimuli" regulations as they focus on fostering experimentation and adopting technological and innovative solutions in the electricity network to favor a more sustainable and cost-efficient service (EURELECTRIC, 2016; Cambini et al., 2016b). Currently, the "innovation-stimuli" regulations target smart grids (SG) and efficiency technologies (Crispim et al., 2014). So far, there is little research on these innovation-stimuli regulations, the exception being Cambini et al. (2020), Haffner et al. (2019), Cambini et al. (2016b), and Marques et al. (2014). Most of this literature is descriptive (EURELECTRIC, 2016; Haffner et al., 2019), apart from Cambini et al. (2016b), who performed a quantitative analysis and

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found a positive effect of the "innovation-stimuli" regulations on investments allocation. However, the study lacks to explore the regulations' effect on innovation outcomes.

To address this gap, we contribute to the literature by first categorizing the stimuli policies of 21 countries and then investigating its effects on patenting activity in the electricity sector by employing a difference-in-differences design. Therefore, we constructed our dataset based on the dispersed literature about innovation-stimuli regulations implemented by the European countries and categorized them using references from Cambini et al. (2016a) and Jamasb et al. (2021). After testing the stimuli-innovation regulation, we find a positive impact of these regulatory tools on innovation outputs in the electricity sector using a two-way fixed effects specification that accounts for the time differences in adopting the regulation.

To decompose the impact and test for additional robustness of our results, we employ the novel group-time treatment effects approach from Callaway and Sant'Anna (2020) and a Zero-Inflated Poisson model. The results confirm the positive average impact from the main specification, but the decomposition shows that for the late-adopter countries with lower patenting activity, the regulatory change does not have the same average impact. Our findings advance the discussion of innovation dynamics in regulated sectors and the role of the regulatory tools in enabling the energy transition.

The study proceeds as follows. Section 2 reviews the literature on innovation-stimuli regulations and their definitions in the electricity sector. Section 3 describes the methodology, outlining the procedure employed for the country's assignment to the treatment and control group and the variables and econometric specification. Section 4 presents the main findings and robustness checks. Finally, we discuss the results and conclude by providing the policy implications of the findings, along with the limitations and future research suggestions.

2. Literature review

The electricity sector has been subject to different waves of regulative reforms that led to an increasing liberalization of the sector regulation during the second half of the 20th century. In the 1960s, the public control of electricity provision was criticized for inefficiencies and the underperformance of the services provided. This perspective was supported by Averch and Johnson (1962), which revealed that the ongoing structure of price incentives led natural monopolies sectors to overinvestments, and scarce incentives to modernize and increase the service and economic performance in the sector (Baumol, 1967; Bailey, 1974).

Therefore, in the 1980s, a movement toward deregulation, privatization, and unbundling in the electricity sector was initiated. This movement entailed to shift the sector control from the public to private providers, arguing that private firms would intensify efficiency and productivity levels in the sector, given their intrinsic impulse toward increasing earnings (Meletiou et al., 2018). To achieve these goals, it was implicitly expected that fostering investments in research and development (R&D) would subsequently enhance innovation outcomes (Jamasb and Pollitt, 2008).

However, the empirical evidence on the effects of liberalization on innovation outcomes is mixed. Some studies indicate that liberalization led to less and more short-term focused research and development in the electricity sector (Poudineh and Jamasb, 2015). Complementary to this finding, Cambini et al. (2016a) show that firms in the sector had more incentives to acquire innovation externally from specialized technology suppliers. Other studies reveal limitations of the liberalization process – related to decreasing levels of regulation – in fostering innovation, which means that countries may suffer from a possible stagnation in innovation after achieving a certain liberalization level threshold (Marino et al., 2019). Moreover, Marino et al. (2019) showed positive effects on innovation in countries that, on average, had experienced a relatively weak reform process and a negative impact in countries which experienced a more drastic liberalization process.

Bauknecht (2011) argues that the current regulation lacks incentives for electricity companies because failing to reduce the risks and additional costs associated with innovation investments. This is primarily because the regulatory lag[1] is too short to benefit companies from the financial results of R&D efforts. Moreover, the literature argues that specific innovation-stimuli regulation can offer adequate incentive to foster innovation in the sector (Poudineh and Jamasb, 2015; Cambini et al., 2016a; Cambini et al., 2016b).

In this context, the innovation-stimuli regulations constitute a regulatory tool that started to be applied in several European countries to explicitly foster research, development, and innovation activities in the electricity firms, as stated in reports of the federation for the European electricity industry – EURELECTRIC (2016) and of the European Commission (Haffner et al., 2019). According to Pollitt et al. (2021), the innovation-stimuli regulations have a more "downstream" level policy nature since they focus on electricity firms' industry learning through the endeavor of experimenting and introducing innovations, particularly targeting SG and efficiency technologies (Crispim et al., 2014).

These technologies are associated with investments in the interaction of transmission and distribution networks to allow intelligent communication monitoring and management systems network, increasing the reliability and reducing energy costs (Marques et al., 2014). Particularly, the SG in the energy transition mitigates the increasing volatility produced by the renewable energy production sources (Lamnatou et al., 2022) because it supports advanced control devices and algorithms to analyze the grid conditions, and it conducts appropriate corrective actions to prevent outages and power quality disturbances. In addition, the SG creates new interfaces and decision support tools by enabling the communication between customers and electricity providers, which allows automatic collection of billing data, faster detection of an outage, and fault location (Luthra et al., 2014).

SG faces many obstacles that prevent its broad adoption by electricity firms. Luthra et al. (2014) and Costa et al. (2017) argue that the immateriality, performance uncertainties, and high coordination complexity, constitute major barriers that hinder SG deployment and maturation because they increase firms' financial risk. To circumvent these obstacles, Luthra et al. (2014) defend the necessity to modify the utilities regulatory mechanism to encourage investments in SG technologies installations. Complementarily, Costa et al. (2017) suggest initiatives for transformational activities, such as R&D, pilot projects, and initial deployment, which are capable of reducing technical uncertainties and accelerating the commercialization of this less mature technology.

These studies endorse the limitations of the existing regulatory schemes, "cost of service" and "incentive regulations", to properly foster R&D in the electricity sector (Égert, 2009). Notaby, the "cost of service" regulations are known for leading to an inefficient operation of the services because it incentivizes overinvestments (Averch and Johnson, 1962), and "incentive regulations" lack in providing targeting incentives to reduce the risks and additional costs associated with innovation initiatives and investments (Bauknecht, 2011).

Cambini et al. (2016b) empirically verified how different price regulations – cost-based, incentive-based, and hybrid regulations – attracted more SG investments and discovered that specialized innovation-stimuli regulations increased investments in SG. On a theoretical level, the benefits of innovation-stimuli regulations application to foster SG, and efficiency in the European electricity sector, were debated by Marques et al. (2014), Costa et al. (2017), and Crispim et al. (2014). To sum up, despite the empirical and theoretical support that innovation-stimuli regulations might incentivize innovation in the electricity sector, no study evaluated the impact of these regulations on innovation output. In the following, we aim to fill this gap in the literature by

[1] The regulatory lag refers to the regulator's time to adjust the utility costs and revenues.

providing empirical evidence of the effects of innovation-stimuli regulation in the European context.

3. Methodology

3.1. Dependent variable: patents

To measure the effect of innovation-stimuli regulation on innovation efforts, we use patents as our dependent variable. Patents constitute a widely employed *proxy* of technological innovation performance since it allows to distinguish between different types of R&D (Haščič and Migotto, 2015). In previous studies discussing regulation and innovation in the electricity sector, patents were used as a *proxy* to analyze technological development (Cambini et al., 2016a; Marino et al., 2019).

Popp (2019) affirms that patents constitute a suitable indicator of R&D activity, since they measure the innovation output, and simultaneously provide a good indicator of R&D activity which constitute an input perspective. Nonetheless, we acknowledge that patents remain an imperfect indicator of innovation, as not all patents lead to technology adoption and patents are at times exclusively used to block competitors rather than to protect new products and processes (Cohen et al., 2000).

Despite the mentioned drawbacks, we use the "Y02" classification system from the Cooperative Patent Classification (CPC).[2] More specifically, we selected the Y02E40 class which refers to "Technologies for an Efficient Electrical Power Generation, Transmission or Distribution" (Table A1 in Appendix A) and we retrieved the data from the Organization for Economic Co-operation and Development (OECD) database,[3] which accounts for the patents application based on the priority date (first application worldwide) by inventor country. According to De Rassenfosse et al. (2013), these data specifications ensure comparability between countries, especially among EU countries. The data is of fractional form, meaning that when the patent has inventors from multiple countries, and the respective share of inventors is allocated to each country.

The Y02E classification scheme has been recently broadly applied to better support patents identification (Costantini et al., 2017; Bel and Joseph, 2018; Hille et al., 2020) because retrieves information related to climate change mitigation technologies and SG (Veefkind et al., 2012; Calel and Dechezleprêtre, 2016; Popp, 2019). In our case, the Y02E40 selection targets transmission and distribution technologies that support electricity system stability and efficiency by improving voltage regulation, balance, sharing lines, and SG. This allows a two-way flow of electricity and digital communications technology. Therefore, the Y02E40 classification was preferred given the innovation stimuli-regulation focus (Cambini et al., 2016a; EURELECTRIC, 2016; Haffner et al., 2019; Cambini et al., 2020), and convergence with the SG patents. Simultaneously, restricting to a more narrow patent class mitigates the potential internal validity risks that could emerge from other policies in place by the analyzed countries.

3.2. Treatment

Our treatment variable is the innovation-stimuli regulation (*RDI*) which constitutes a dummy variable coded as one when country *i* has an innovation-stimuli regulation in place at year *t* and zero otherwise.

The empirical analysis comprises 21 European countries and covers the period from 1991 to 2016. Countries selected for this study were first classified into two groups based on the innovation-stimulus initiatives in the European electricity sector identified by Haffner et al. (2019). Then, we organized the country-level innovation-stimulus mechanisms into four different categories: (a) explicit, (b) implicit, (c) no reference, and (d) no evidence.

From this selection, we used (a) as the treatment group and (b), (c), and (d) as the control group. More specifically, we chose countries with an explicit reference to concepts linked to investments in innovation in the electricity sector in their national or sectorial legislation. Data on innovation-stimuli regulations features of each country was obtained through existing literature on the subject and websites, reports, norms, and laws available from the websites of governments and regulatory authorities.

Table 1 presents additional information regarding the regulatory authority, the innovation-stimuli regulation, its year of implementation, the level of application, being either at the level of Transmission System Operators (TSO) and/or Distribution System Operators (DSO), as well as the different types of incentive mechanisms. It is important to highlight that the adoption of different innovation-stimuli regulation mechanisms illustrates the adaptation strategy of the national regulatory authority in shaping this regulatory tool to the realities of their domestic electricity sectors (EURELECTRIC, 2016). Furthermore, the increasing number of EU countries implementing the innovation-stimuli regulations is related to guidelines published by the European Parliament and the Council, recommending the promotion of energy efficiency by the EU Member States' regulatory authorities to develop innovative pricing formulas, or introduce smart grids, when appropriate.[4]

In the regulatory landscape analyzed, we identified four different types of approaches to foster innovative initiatives in the electricity sector and to classify them, we proposed four different categories based on previous studies from Cambini et al. (2016a) and Jamasb et al. (2021): (a) Innovation Allowance for Network Operator; (b) Funding for Projects; (c) WACC-based approach; and (d) Revenue, Incentives, Innovation, and Outputs (RIIO). The following paragraphs detail them.

The most common of these approaches is the "**Cost-pass through**" found in the following countries: **Belgium**, **Finland**, **France**, **Germany**, **Norway,** and **Portugal**. In these countries, the regulated companies – TSO and DSO – can pass on the R&D project expenses, originally partially funded by public subsidies, directly to the customers. The amount of subsidy per firm has a ceiling based on the revenue acquired in that specific year. These expenditures are beforehand approved by the regulatory authority or governmental body.

The second most used approach, "**Funding for Projects**" is applied by **Denmark, Ireland,** and **Sweden**, in which R&D projects are proposed by private companies and universities and granted funding to develop and demonstrate new and innovative energy technologies. These fundings focused on research and development activities aiming to develop and improve environmentally friendly and energy-efficient transmission and distribution technologies.

One country-specific approach is the "**WACC-based approach**" employed by Italy, which refers to an additional incentive based on the weighted average cost of capital (WACC). In this case, the support for innovative projects is given by the Italian Regulatory authority for electricity, gas, and water (AEEGSI) through a WACC premium of 2% for 12 years to support Smart Grids, integration of distributed generation and conversion, and storage systems.

Lastly, in 2005 the **United Kingdom (UK)** was the first country to institute an innovation funding incentive. In an earlier version of this fund, the regulation would establish financial assistance on cost eligible to up to 0.5% of the company's revenue on R&D projects (Jamasb and Pollitt, 2011). In 2010, the UK intensified its incentives through the **Revenue, Incentives, Innovation, and Outputs (RIIO)**, which

[2] The CPC is an extension of the IPC and is based on specific technology groupings joint by common subject matter. This classification scheme was developed by the European Patent Office (EPO) and the United States Patent and Trademark Office (USPTO).

[3] The records on patent data from OECD database rely on the Worldwide Statistical Patent Database (PATSTAT) maintained by the European Patent Office (EPO).

[4] Directive 2009/72/EC and 2012/27/EU from the European Parliament and of the Council.

Table 1
Countries in the Treatment and its innovation-stimuli regulation.

Country	Regulatory authority	Innovation-stimuli regulation	Year	DSO/TSO	Incentive mechanism
Belgium	Commission for Electricity and Gas Regulation (CREG)	Article 12 § 2 of the Electricity Law	**2014**	TSO	Cost-pass through
Denmark	Danish Utility Regulator (DUR) and the Danish Energy Agency (DEA)	Act on EUDP of 22 December 2010	**2010**	TSO and DSO	Funding for Projects
Finland	Energy Authority (EA)	Electricity Market Act (588/2013)	**2013**	TSO and DSO	Cost-pass through
France	Commission de Régulation de l'Énergie (CRE)	Tarif d'utilisation du réseau public d'électricité (TURPE) 4	**2014**	DSO	Cost-pass through
Germany	Bundesnetzagentur (BnetzA)	Incentive regulation 2007 (ARegV)	**2007**	TSO and DSO	Cost-pass through
Ireland	Commission for Regulation of Utilities (CRU)	CER/15/295 and CER/16248	**2016**	TSO and DSO	Funding for Projects
Italy	Italian Regulatory authority for electricity, gas, and water (AEEGSI)	Deliberazione ARG/elt 39/10	**2010**	TSO and DSO	WACC-based approach
Norway	Norges vassdrags- og energidirektorat (NVE)	Energy Act (n. 50 of 1990)	**2013**	DSO	Cost-pass through
Portugal	Entidade Reguladora dos Serviços Energéticos (ERSE)	Regulamento n. 496/2011	**2012**	DSO	Cost-pass through
Sweden	Swedish Energy Markets Inspectorate (Inspectorate)	Ordinance n. 761/2008	**2008**	TSO	Funding for Projects
United Kingdom	The Office of Gas and Electricity Markets (Ofgem)	Innovation Funding Incentive (IFI) 2005	**2005**	TSO and DSO	RIIO

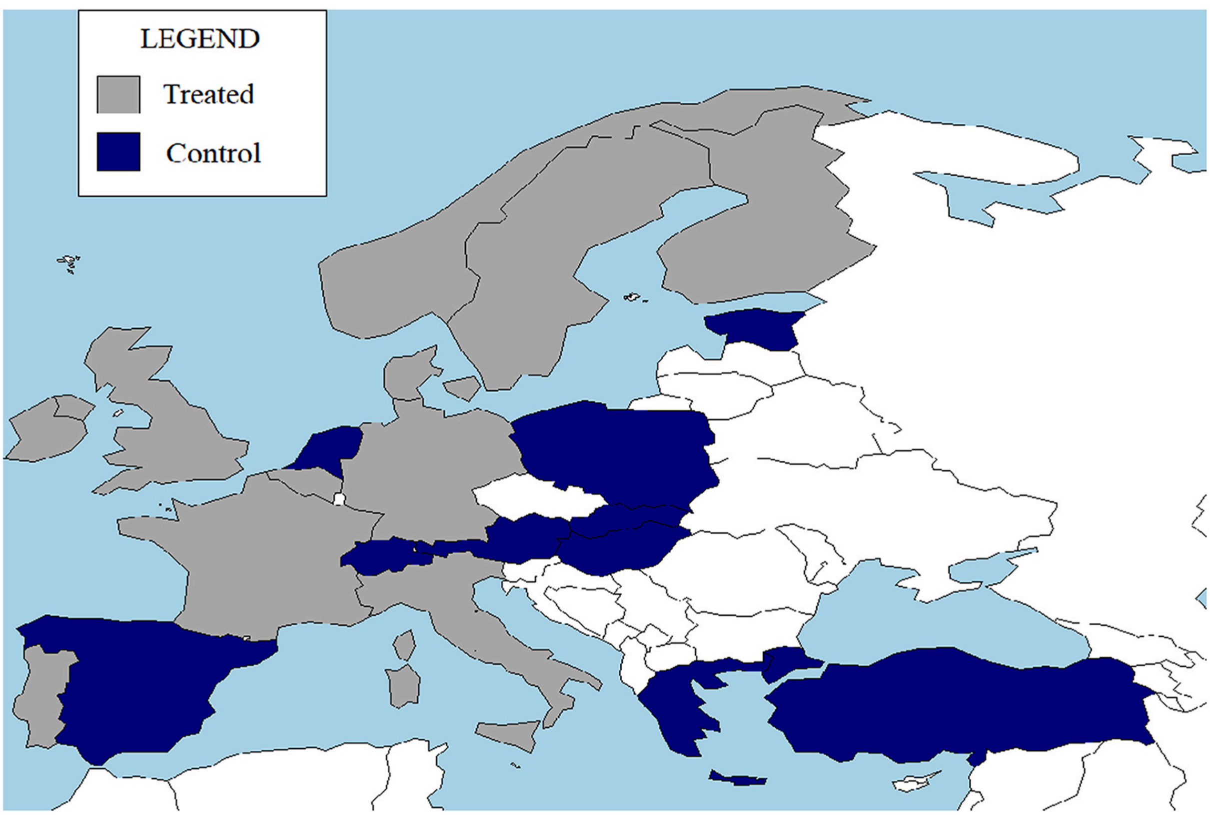

Fig. 1. Spatial representation of the countries in treated and control groups.

stimulates high technological and risky initiatives through three different mechanisms: Network Innovation Allowance (NIA), Network Innovation Competition (NIC), and Innovation Roll-out Mechanism (IRM).

The NIA constitutes a revenue allowance between 0.5%–1% of base revenues for each company to finance small R&D and demonstration projects. The NIC is a competition to select large development and demonstration projects performed by TSOs and DSOs. The IRM refers to an incentive only allowed to be funded if the roll-out of trialed innovations presents environmental benefits and provides value for consumers (Ofgem, 2021).

To the best of our knowledge, the other following countries in our sample: Austria, Estonia, Greece, Netherlands, Poland, Portugal, Slovak Republic, Spain, Turkey, and Switzerland lacked explicit innovation-stimuli regulations and therefore were allocated to the control group. Fig. 1 presents the countries on our sample that were allocated in treatment and control group.

3.3. Control variables

To control for any remaining time-varying differences across units after controlling for time and unit-fixed effects, a difference-in-difference in differences (DiD) estimation can be enhanced through the inclusion of additional control variables (Card and Krueger, 1994). The inclusion of relevant controls can strengthen the equal trends assumption, which is the key assumption for DiD, and improve the precision of the treatment effect estimation. Prior to the selection of our final specification, we tested the relevance of variety of such control variables for which an ex-ante inclusion would potentially be justified due to a theoretical link between these variables and our outcome variable.

First, we selected research, development, and demonstration (RD&D) budget (*Budget*), and R&D personnel (*Personnel*) as input indicators of innovation process. Both variables were retrieved from the IEA, OECD, and EUROSTAT databases. The energy technology RD&D budget encompasses research, development, and demonstration expenditures related to the production, storage, transportation, distribution, and rational use of all forms of energy from the public and private sectors. We considered RD&D Budget as it is likely to influence the overall inventive activity (Dechezleprêtre et al., 2011). The R&D personnel refers to full-time personnel allocated to R&D activities in "electricity, gas, steam, and air conditioning supply", since there is no information disaggregated by country and year exclusively focusing on electricity RD&D personnel. At the same time, a report from Czako (2020) demonstrates that in the category "electricity, gas, steam, and air conditioning supply", electricity-related activities corresponded for more than six times more jobs than the other two categories each.

Other independent variables considered were market regulation in the electricity sector (*Market_reg*), and electricity consumption (*Elec_consum*). We include the former variable to control the level of product market regulation, which is a proxy for the liberalization process in the electricity sector in the different EU countries, and the later to account for major macroeconomic effects related to the national electricity sector (Cullmann and Nieswand, 2016). The market regulation indicator of the electricity sector was developed by OECD in their Product Market Regulation dataset (Conway et al., 2006; Koske et al., 2015). This indicator measures the regulatory intensity of anti-competitive regulation through an Index (0–6) based on entry regulation,[5] public ownership,[6] vertical integration,[7] and market structure.[8] This index is broadly used in studies dealing with the interface of regulation and innovation and there is an intense discussion in the literature regarding the influence of the regulation level on the countries' overall stimuli to innovate (Cambini et al., 2016a; Marino et al., 2019),[9] for this reason we decided to control this aspect.

Finally, we also considered electricity consumption to accounts for potential differences in the growth of the domestic electricity consumption, which may influence innovation incentives (Churchill et al., 2021). Here we used the sum of gross production, imports, and subtraction of exports and losses, expressed in terawatt-hour (TWh). According to Giest (2020), the increase in electricity consumption constitute a significant factor that encourage the use of smart meters and technologies, and is a common variable employed in this type of model (Hille et al., 2020; Cambini et al., 2016a). Lastly, we also had considered gross domestic product (GDP), which controls for the size of the countries and ensure the comparability of the patent output between the EU countries (Polemis and Tselekounis, 2021), however due to multicollinearity problems it was excluded from our model.

After performing sensitivity test to assess the significance of all these independent variables (the results are on Table B1 in Appendix B), we decided to keep only the variable RD&D Budget, as this is the only covariate that was consistently significant across different specification and we want to avoid an overparametrization of our model through the inclusion of non-relevant control variables on our model. Additionally, to control for external effects on innovation in the electricity sector, we include time- and country-fixed effects in our model.

3.4. Econometric specification

To account for the differences in the timing of the policy introduction, we are using a difference-in-difference model with two-way fixed effects, which takes the following form:

$$Y_{it} = \beta^{*}RDI_{it} + \gamma^{*}Budget_{it} + \vartheta_i + \delta_t + \varepsilon_{it} \tag{1}$$

In this model, i refers to the country and t to the year. Y_{it} refers to the number of patents. RDI_{it}, is the binary dummy variable indicating whether the country has an innovation-stimuli regulation (1) or not (0) at time t. Our DiD estimator is β and measures the impact of innovation-stimuli regulation on innovation interaction. δ_t,and ϑ_i control unobserved country and time fixed effects respectively. The remaining variable $Budget_{it}$ controls for remaining time-varying, country specific variation due to differences in the RD&D budgets. ε_{it} is the idiosyncratic error term. The panel data set is unbalanced due to some missing values on the control variable.

Despite having patent count data as a dependent variable, we are using a linear two-way fixed effects OLS model as our main specification for the following two reasons. First of all, Puhani (2012) demonstrates that the DiD estimation in a nonlinear model does not provide the assumption that the cross difference is zero for the expected potential outcome Y0. As a consequence, the nonlinear parametric restriction on that cross difference, does not represent the treatment effect. Second, we are using fractional data which is not composed exclusively of integers. Wooldridge (1999)[10] cautions against the usage of Poisson or negative non-binomial models in such cases. Nonetheless, to refute any potential criticism that our results may be dependent on our model choice, we also perform a zero-inflated count model regression. We have to use the zero-inflated rather than the normal poisson model because our dependent variable has 46% zeros.

In addition to the two-way fixed effects specification, we measure the treatment effect across parts of the treatment group. Therefore, we employ the so-called group-specific treatment effect estimation by Callaway and Sant'Anna (2020), whereby the average treatment on the treated is estimated separately for each period in which a country or a group of countries enters treatment.

According to Steigerwald et al. (2021), this approach verifies different treatment effects depending on the adoption period. Due to the

[5] The Entry Regulation is measured by the terms and conditions of third-party access to the electricity transmission grid determined – the degree of liberalization of the wholesale market for electricity and the minimum consumption threshold that consumers must exceed to choose their electricity supplier.

[6] The Public Ownership measures the ownership structure of the largest companies in the electricity industry's generation, transmission, distribution, and supply segments.

[7] The Vertical Integration measures the degree of vertical separation between the transmission and generation segments of the electricity industry and the degree of vertical integration in the electricity industry.

[8] The Market Structure measured the market share of the large companies in the sector. In this index, low values indicate lower levels of regulation and probably higher levels of competition. In contrast, high values are associated with a less competitive and more closed market.

[9] Given the discontinuity of the index between 2013 and 2018, we employed a time series developed by OECD to connect both years (Vitale et al., 2018).

[10] See Jeffrey Wooldridge and Joao Santos Silva in the Statalist blogpost, accessed on July 10th, 2022.

limited sample size of only 21 countries, we divided our treatment countries into "early adopters" and "later adopters". The resultant group-specific ATT is defined for each group entering treatment at time s ≤ t as is given by the following equation:

$$ATT_t^s = \in \left[\tau_{it} \mid t_i^* = s\right] \tag{2}$$

4. Results and discussion

4.1. Descriptive statistics, identification strategy, and assumptions

Table 2 summarizes all the variables in our model: patents, and RD&D budget. The variables present the total number of values of the treatment and control groups and the mean and standard deviation.

Despite the differences in terms of the means of the treatment and control group, parallel trends are sufficient as an identification assumption in the DiD setting. Fig. 2 shows the average number of patents for both groups and supports the assumption in our case. Prior to introducing the first innovation-stimuli regulation in 2005, the development of the outcome variable is relatively parallel with similar minor upward and downward deviations. The trends started to diverge after 2009, shortly after the first European countries introduced innovation-stimuli regulations. We also ran an event study regression which confirms the graphical results. The difference in means only start to diverge in 2007 and difference are non-significant until 2010, which is well after the first wave of innovation-stimuli regulations are introduced (see Fig. B2 in Appendix B).

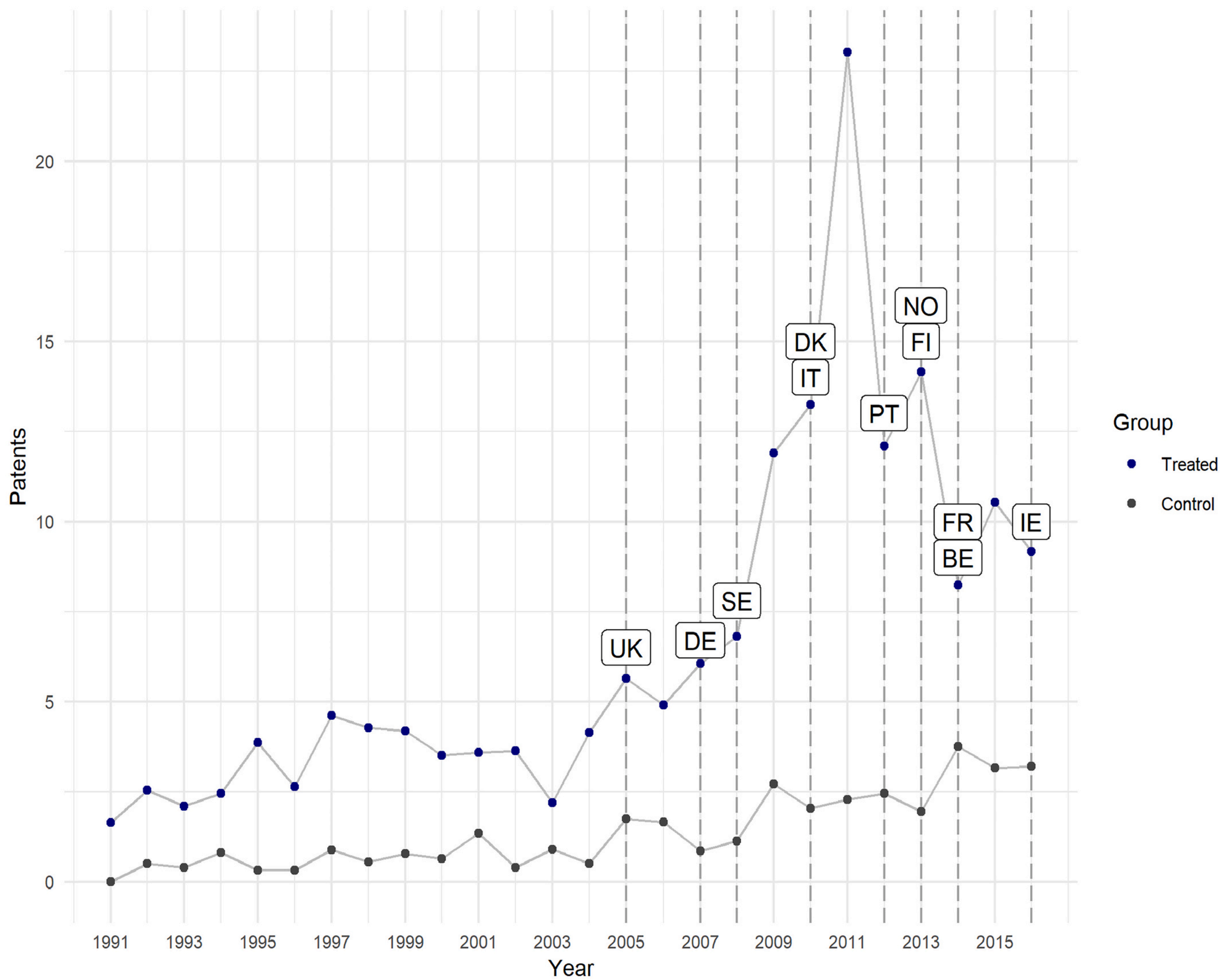

Fig. 2. Innovation-stimuli regulation by country and patent average (1991–2016).

Table 2
Summary statistics of the country-level variables between 1991 and 2016.

Variable	Statistic	Treated	Control	Description
Patents	N	286	260	Technologies for an Efficient Electrical Power Generation, Transmission or Distribution Patents (OECD)
	Mean	6.582	1.355	
	SD	13.177	2.725	
RD&D Budget	N	261	183	Research, Development, and Demonstration (RD&D) Budget expended by public and private sector in USD 2019 prices and PPP (IEA)
	Mean	358.73	129.412	
	SD	418.118	102.582	

Note: 1. The panel is unbalanced due to missing values in some variables.

Fig. 3 illustrates the development of the group means of the control variable of the treated and control group during the time analyzed (1991–2016). RD&D budget increases in both groups but more consistent among the treated countries. The increase in the treatment group might be partially related to the research and innovation financial incentives given by the introduction of stimuli-innovation regulation in these countries.

4.2. Regression results

We performed a difference-in-difference (DiD) analysis to further investigate the indications provided by our descriptive results and to obtain a causal estimation of the impact. The results are presented in Table 3. The first two models (1) and (2) are the regressions without controls. Model (1) is the DiD without fixed effects, and Model (2) is the DiD with the two-way fixed effects. The following models (3), (4), and (5) include the controls. Model (3) represents the DiD with time-fixed effects, Model (4) constitutes DiD with country fixed effects, and Model (5) is our final model with the two-way fixed effects model.

All five models indicate a positive and significant effect of the innovation-stimuli regulation on patents. As expected, the point estimates decrease when we include the control variable, but the effect remains significant in all specifications. We tested for the presence of time and country-fixed effects and found significance for both. In Model (5) which constitutes our final specification, the average treatment on the treated is of 7.4 patents. Model (3) and (4) are presented to demonstrate the evolution of the estimates through the inclusion of the fixed effects. Regarding our control variable, the RD&D budget have in most of the models a consistent and significant effect. On average, an

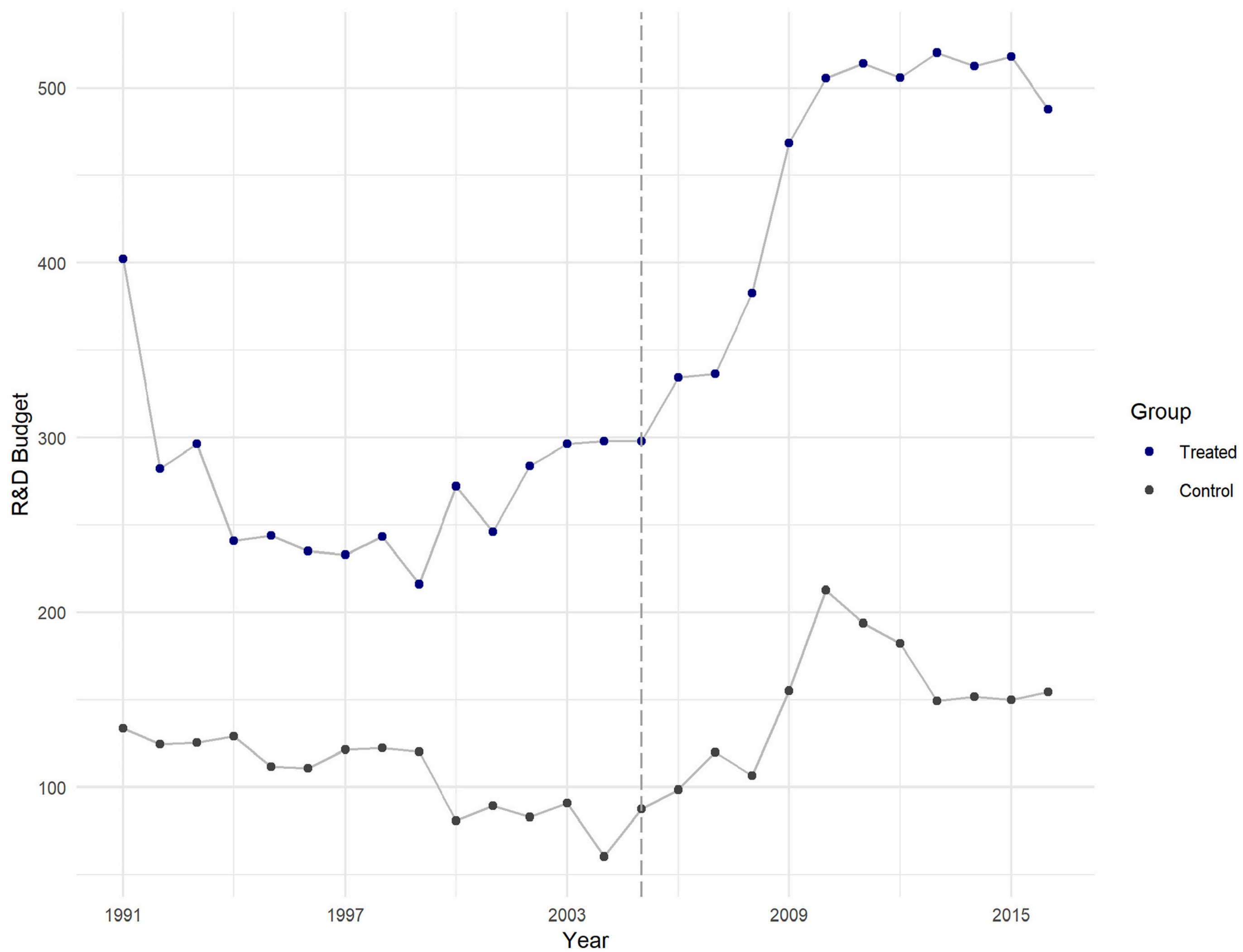

Fig. 3. The average of RD&D Budget in treated and control group (1991–2016).

Table 3
OLS, time fixed-effects, country fixed-effects, and two-way fixed effects.

	Dependent Variable: Patents "Technologies for an Efficient Electrical Power Generation, Transmission or Distribution" (Y02E40)				
	(1)	(2)	(3)	(4)	(5)
Innovation-stimuli regulation	15.575***	9.531**	13.720***	6.691***	7.461**
	(2.867)	(3.920)	(4.709)	(2.590)	(2.938)
RD&D Budget			0.010	0.018***	0.015*
			(0.007)	(0.004)	(0.008)
Constant	2.325***				
	(0.210)				
Time FE	NO	**YES**	**YES**	NO	**YES**
Country FE	NO	**YES**	NO	**YES**	**YES**
Observations	546	546	444	444	444
R2	0.241	0.124	0.302	0.278	0.164
Adjusted R2	0.240	0.043	0.256	0.240	0.065
F Statistic	173.505*** (df = 1; 544)	70.652*** (df = 1; 499)	90.085*** (df = 2; 416)	81.285*** (df = 2; 421)	38.985*** (df = 2; 396)

Notes: 1. *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.
2. Cluster-Robust Standard Errors (White-Arellano) correction for cross-sectional dependence, serial correlation, and heteroskedasticity in all the models.

increase of 100 Mio. USD in R&D Budget is associated with 1.5 additional patent applications.

Comparatively, other more diffused regulatory tools, such as tax reductions and tax credits that present a rather indirect and less distinguishing effect, depending on the firm's actual market penetration, the renewable energy quotas demonstrate insignificant effect on innovation outputs (Hille et al., 2020). Feed-in tariffs present also a divergent behavior depending on the technology, and solar technologies, usually benefit from them (Nicolli and Vona, 2016). Studies also distinguish the benefits of demand subsidies and public support for R&D on emerging technologies (Nicolli and Vona, 2016; Costantini et al., 2017). Hence, our findings align with other studies that support the impact of R&D budget on innovation output (Cambini et al., 2016b; Dimos and Pugh, 2016) and the implementation of specific energy technology and innovation policy Marino et al. (2019).

To better understand the temporal development of the innovation outcome on the treatment and control group, we compared the evolution of patents' increment throughout our time period and grouped them in the treatment and control group (Figs. 4 and 5). Fig. 4 demonstrates an increment of patents when the innovation-stimuli regulations were introduced in the treatment group between 2006 and 2010. Nevertheless, in the following period, the control group (Fig. 5) during 2011–2016 have a higher growth rate (100%) than the treatment group (80%).

To further explore the composition of the effect, we analyzed the innovation-stimuli regulation among the treatment group in different periods using the group-specific effects approach proposed by Callaway and Sant'Anna (2020). As mentioned before, the group-specific effect model aims to include an additional layer on the DiD approach by assessing whether the DiD estimate is dependent on the timing of the treatment. To perform this analysis, we divided the treatment group into two, the "early-treated" and "late-treated", based on the period of adoption of the innovation-stimuli regulation.

The "early-treated" are countries which introduced their innovation-stimuli regulation from 2005 to 2010, and the "late-treated" those that introduced them from 2011 onwards. Their assignment into different groups based on the introduction of innovation-stimuli regulation enables us to verify the average treatment effects over time for that specific group.

The results from the group-time average treatment effect, which shows the average treatment effect on the treated (ATT) for (a) all countries that adopted the innovation-stimuli regulation, (b) the "early adopters", and (c) "late adopters". Confirming the results from the regression analysis, the overall average treatment of the treated group is positive and significant, with an ATT of 5,01. The group decomposition demonstrates that the overall effect is driven by the "early adopters", with an ATT of 10,99. The point estimate of the late adopters is close to zero and not statistically significant (see Fig. C1 in Appendix C).

Hille et al. (2020) in their study on Y02E patents also stressed the

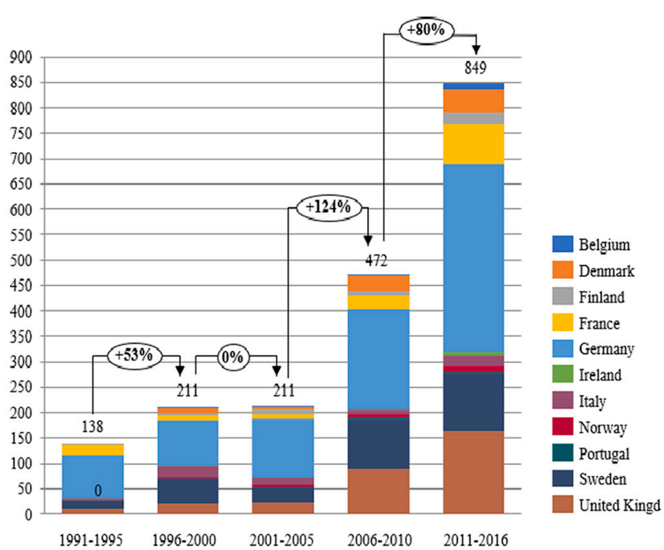

Fig. 4. Patents increment (1991–2016): treatment group.

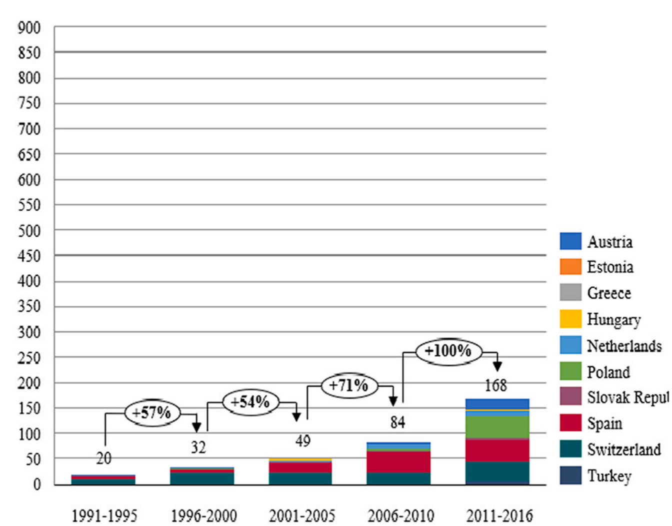

Fig. 5. Patents increment (1991–2016): control group.

decline in patent applications for late adopters' countries, between 2011 and 2015 despite the rising adoption of regulatory instruments. The authors affirm that during this period the different regulatory mechanisms were implemented in countries with less dynamic technological activities, and consequently with a low patenting rate. This result demonstrates that the innovation-stimuli regulations effects were not the same among all the countries from our sample. Notwithstanding, the additional insights about the decomposition of the effect, the results should be interpreted with caution, as the groups used for the group-time specific models are very small, and especially in the late-adopter groups, the effect was measured over a shorter time-period.

Figs. 6 and 7 illustrate this trend by showing the differences in the average number of patents between the "earlier adopters" and "later adopters". The graphs demonstrate a 128% increase in the number of patents for the early adopters during the first innovation-stimuli regulation implementation and positive but somewhat slower growth after that, while the late adopter group experiences much more robust growth in the last period (2011–2016). Furthermore, when comparing the "later adopters" and the control group (Fig. 5), there is a superior rate of patent increment among the later adopters. Fig. 7 indicates that despite the non-significant average treatment effect on the "late-group", patents substantially increased after introducing innovation-stimuli regulations.

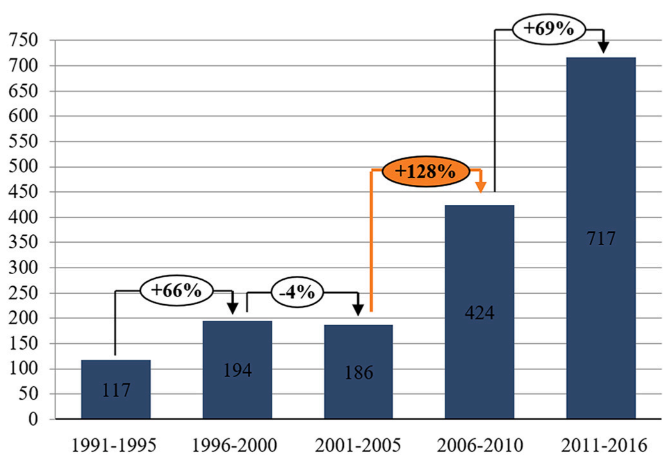

Fig. 6. Patents increment (1991–2016): early adopters.

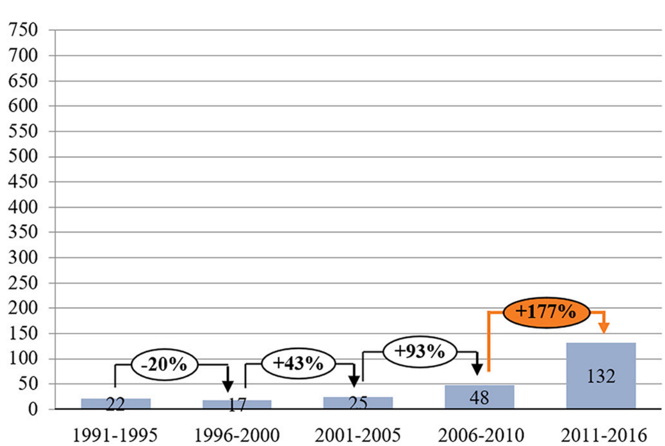

Fig. 7. Patents increment (1991–2016): late adopters.

4.3. Robustness tests

As an additional robustness check we estimate the Zero-Inflated Poisson model. Therefore, we first transformed our fractional patents into integers by rounding up and performed a Zero-Inflated Poisson regression. We opt for estimating the Zero-Inflated Poisson because our variable is overdispersed due to the existing large number of "zeros" in our patents (46,3%), and the negative binomial model does not account for serial correlation (present in our data).

Comparatively, Cameron and Trivedi (2013), reveals that efficiency gains relative to Poisson regression are likely inexistent or small in the case of fixed effects and fixed effect negative binomial model is flawed and advice uses Poisson panel fixed effects (Guimarães, 2008; Wooldridge, 1999). The results of our Zero-Inflated Poisson model are in Table 4. Model (1) is the DiD without fixed effects, and Model (2) and (3) have country and time fixed effects, respectively. Model (4) contains two-way fixed effects.

The result from Model (4) are fairly robust to changes in the patent count approach and demonstrate a significant effect of 22,50% increase ((eˆ0.203–1)*100) for the countries that have an innovation-stimuli regulation in place. The zero-inflated part of our model is not significant in the two-way fixed model (4) which means that innovation-stimuli regulation does not have a significant impact on having zero patents. This provides some evidence to the argument by Hille et al. (2020) that countries need already a certain level of technological development and capacity in place to benefit from the introduction of the innovation-stimuli regulation.

Table 4
Zero-Inflated Poisson.

	Patents: technologies, rounded			
Poisson	(1)	(2)	(3)	(4)
Innovation-stimuli regulation	1.387***	0.807***	1.282***	0.203**
	(0.042)	(0.053)	(0.074)	(0.094)
	$t = 32.965$	$t = 15.298$	$t = 17.388$	$t = 2.163$
Zero-Inflated Poisson				
Innovation-stimuli regulation	−2.469***	−2.149***	−1.839***	0.503
	(0.475)	(0.706)	(0.517)	(0.971)
	$t = -5.195$	$t = -3.041$	$t = -3.555$	$t = 0.518$
Observations	546	546	546	546
Log Likelihood	−2028.186	−1227.821	−2211.10	−1004.880
AIC	4064.371	2543.642	4530.216	2197.760

Notes: 1. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.
2. The control variable (RD&D budget) was not included because to limited sample size, did not allowed the converge of our estimations.

5. Conclusions and policy implications

Employing a difference-in-differences estimation on a dataset covering 21 European countries between 1991 and 2016, we find that innovation stimuli regulation has positively impacted patent applicants in the sector of electricity distribution and transmission.

The findings complement the evidence of Cambini et al. (2016b) about the positive impact of this innovation-stimuli regulation on investment, and underline the positive effects expected by introducing them in the countries' regulatory framework. Nonetheless, early adopters seem to benefit more from the introduction of innovation-stimuli regulations than late-adopters. While we are not fully certain about the reasons for this difference, we suspect that it could be related to the country's technological capacity for patenting activity (Hille et al., 2020), or differences in the innovation-stimuli regulation mechanism adopted.

Overall, the paper contributes to underline the effects of innovation-stimuli regulations, which target to reduce the technological and financial risks of the SG (Luthra et al., 2014; Costa et al., 2017), are producing on average in terms of innovation outputs.

Comparatively, the innovation-stimuli regulation seems more adequate as a regulatory tool to stimulate SG than other well-known policies like renewable energy quotas, feed-in tariffs, and carbon tax, which are focused on stimulating more mature technologies and which are placed in the energy generation segment, such as wind and solar (Nicolli and Vona, 2016; Costantini et al., 2017).

In terms of policy implication, given the consistent average effect demonstrated in the DiD estimations, it contributes to state the necessity of specific energy technology and innovation regulation to foster certain technologies that are considered beneficial for society (Marino et al., 2019; Hille et al., 2020). Under this perspective, the innovation-stimuli regulation seems to constitute a prominent regulatory tool, especially in the case of SG, which are praised as a solution for the volatility challenges imposed for an increasing share of renewables in the electricity matrix, among other advancements. Nonetheless, the implementation of SGs is rather slow and the face several challenges (Lamnatou et al., 2022).

Hence, the paper does not exhaust the discussion of innovation-stimuli regulation but contributes to understand these new regulatory instruments in the SG technologies. In this respect, to proper understand the combination of innovation-stimuli regulation and technological performances a continuous integration of complementary quantitative and qualitative research efforts is required to further comprehend the extensions of its effects.

This study is a first attempt to empirically assess the impact innovation-stimuli regulation and there are of course certain limitations to our results. We are estimating the average impact of innovation-stimuli regulation introduction and are therefore unable to say anything about how different policy design elements impact innovation outcomes, as our sample is too small to make further sub-sample analysis. Moreover, our study focuses on innovation output measures.

For future studies it would be desirable to analyze the effects of the different innovation-stimuli regulation, assess their impacts on innovation inputs and expand the analysis in terms of countries outside Europe. Furthermore, country-specific analyses could help to detect potential thresholds in technological capacity to benefit from the innovation-stimuli regulations.

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CRediT authorship contribution statement

Beatriz Couto Ribeiro: Conceptualization, Methodology, Software, Validation, Data curation, Visualization, Writing – original draft. **Luciane Graziele Pereira Ferrero:** Methodology, Software, Writing – review & editing. **Adriana Bin:** Conceptualization, Supervision, Writing – review & editing. **Knut Blind:** Supervision, Writing – review & editing.

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Appendix A. Patent classification

Table A1
IPC classification - technologies for an efficient electrical power generation, transmission or distribution (Y02E40).

Description	Code
Climate Change Mitigation Technologies Related to Energy Generation, Transmission or Distribution	Y02E
5. TECHNOLOGIES FOR AN EFFICIENT ELECTRICAL POWER GENERATION, TRANSMISSION OR DISTRIBUTION	Y02E40
5.1. Superconducting electric elements or equipment	Y02E40/ 60–69
– Superconducting generators: Superconducting synchronous generators; Superconducting homopolar generators	
– Superconducting transmission lines or power lines or cables or installations thereof - Superconducting transformers or inductors	
– Superconducting energy storage for power networks, e.g. SME, superconducting magnetic storage	
– Protective or switching arrangements for superconducting elements or equipment	
– Current limitation using superconducting elements, including multifunctional current limiters	
5.2. Not elsewhere classified	
Flexible AC transmission systems [FACTS]	Y02E40/ 10–18
– Static VAR compensators [SVC], static VAR generators [SVG] or static VAR systems [SVS], including thyristor-controlled reactors [TCR], thyristor-switched reactors [TSR] or thyristor-switched capacitors [TSC]	
– Thyristor-controlled series capacitors [TCSC]	
– Static synchronous compensators [STATCOM]	
– Unified power flow controllers [UPF] or controlled series voltage compensators	
Active power filtering [APF]	Y02E40/ 20–26
– Non-specified or voltage-fed active power filters	
– Current-fed active power filters; using a multilevel or multicell converter	
Reactive power compensation	Y02E40/ 30–34
– Reactive power compensation; using synchronous generators; for voltage regulation	
Arrangements for reducing harmonics	Y02E40/40
Arrangements for eliminating or reducing asymmetry in polyphase networks	Y02E40/50
Smart grids	Y02E40/70
– Systems characterized by the monitoring, control or operation of energy generation units, e.g. distributed generation [DER] or load-side generation; Systems characterized by the monitoring, control or operation of flexible AC transmission systems [FACTS] or power factor or reactive power compensating or correcting units; Computing methods or systems for efficient or low carbon management or operation of electric power systems	

Source: OECD (2021).

Appendix B. Sensitivity and assumptions tests

Table B1
Sensitivity test of the control variables.

	Dependent variable: patents "technologies for an efficient electrical power generation, transmission or distribution" (Y02E40)					
	(1)	(2)	(3)	(4)	(5)	(6)
Innovation-stimuli regulation	7.461*** (2.938)	8.582** (4.021)	9.229** (3.956)	9.693** (3.902)	7.452** (3.375)	9.307** (3.863)
RD&D Budget	0.015* (0.008)				0.017** (0.008)	
R&D Personnel		−0.001 (0.003)			−0.001 (0.003)	
Market Regulation			0.638 (0.697)			0.861 (0.665)
Electricity Consumption				0.0005 (0.0004)		0.001 (0.0004)
Time FE	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Country FE	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Observations	444	322	546	546	273	546
R^2	0.164	0.081	0.127	0.134	0.140	0.140
Adjusted R^2	0.065	−0.071	0.045	0.052	−0.038	0.057
F Statistic	38.985*** (df = 2; 396)	12.228*** (df = 2; 275)	36.382*** (df = 2; 498)	38.705*** (df = 2; 498)	12.287*** (df = 3; 225)	27.113*** (df = 3; 497)

Notes: 1. $*p < 0.1$; $**p < 0.05$; $***p < 0.01$.
2. Cluster-Robust Standard Errors (White-Arellano) correction for cross-sectional dependence, serial correlation, and heteroskedasticity for all models.

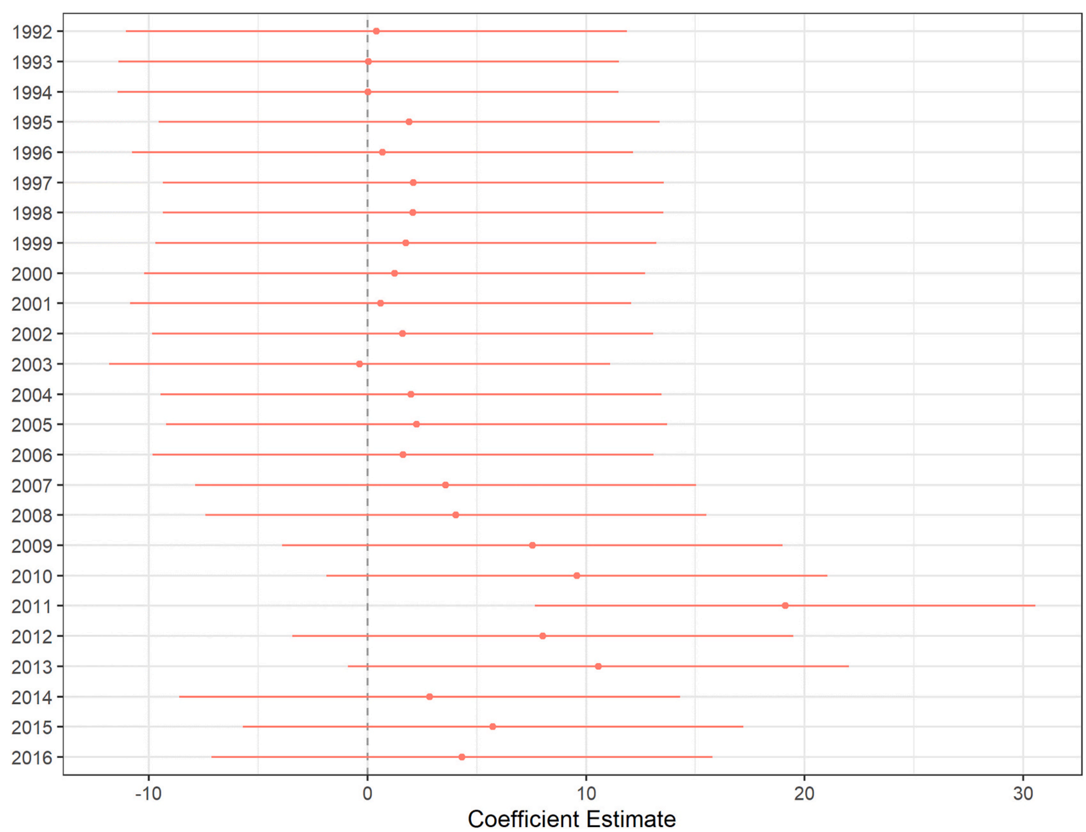

Fig. B2. Event study, coefficient estimation (1992–2016).

Appendix C. Group-specific effects

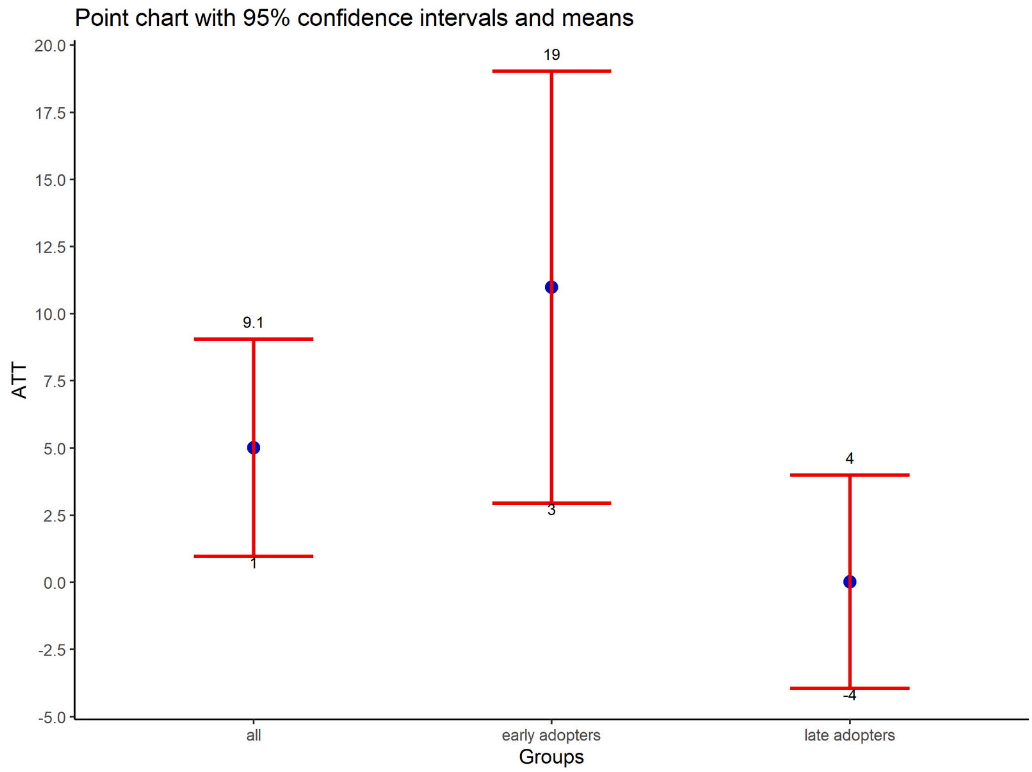

Fig. C1. Average treatment effect in all the countries that adopted the innovation-stimuli regulation countries and Early and Late Adopters.
Notes: 1. Point chart with 95% confidence intervals and means. 2. The group-time average treatment effect model does not include the control variables.

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2022.106352.

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