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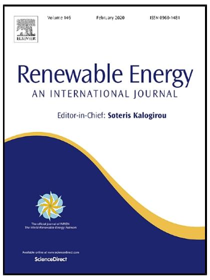

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Fostering Innovation in Renewable Energy Technologies: Choice of policy instruments and effectiveness

Alkis Pitelis[1], Nicholas Vasilakos[2] and Konstantinos Chalvatzis[3]

[1] *Norwich Business School, University of East Anglia, NR4 7TJ, Norwich, UK.*

Norwich Business School, University of East Anglia, NR4 7TJ, Norwich, UK.

[3] *Norwich Business School, University of East Anglia, NR4 7TJ, Norwich, UK. Email address:* n.vasilakos@uea.ac.uk

*Corresponding author: Nicholas Vasilakos, n.vasilakos@uea.ac.uk

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Abstract:

This paper assesses the effectiveness of different types of renewable energy policies (REP) in fostering innovation activity in the OECD electricity sector over the period 1990-2014. More specifically, we collect and analyse data on policy intervention, innovation activity (patent counts per type of renewable technology) and performance for 21 OECD countries from 1990 to 2014. Using the specific characteristics of each policy, we identify all REP in our sample and categorise them to one of three distinct policy types: technology-push, demand-pull, and systemic policy instruments. We then analyse the effects of policy intervention on innovation, by type of policy instrument and by type of technology. Our results show very clearly that one size does not fit all. Innovation activity is found to be more responsive to demand-pull policy instruments only for some technologies (e.g. geothermal), whereas for others a more mixed approach maybe more effective (e.g. wind). And sometimes policies that are designed to target only one technology are more effective in fostering innovation than multi-technology ones (as in the case of solar). Overall, we find that demand-pull policies have been more effective than any other type of policy intervention in driving innovation in renewable energy technologies.

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Keywords: Renewable Energy Innovation; Renewable Energy Technologies; Policies and Instruments; Patents

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1. Introduction

The environmental and economic challenges relating to the use of fossil fuel, alongside a realisation that market forces alone are unlikely to suffice to drive requisite energy transitions, have motivated several governments to adopt Renewable Energy Policies (REP). The use of such policies has been argued by many as an effective way to mitigate both greenhouse gas emissions and other air pollutants. That has stimulated a rather substantial public policy intervention for the renewable energy (RE) sector (Stern, 2007), and it has motivated debates about the role of the relative advantages of markets and governments (public policy) in bringing about desired environmental outcomes.

By way of example, by 2015 as many as 164 countries worldwide had adopted at least one type of policy associated with RE (Nachmany et al, 2017). Since their emergence in the 1970s, REP have taken different forms, ranging from government announcements to legally binding obligations (Kieffer & Couture, 2015). The OECD distinguishes between two waves of REP. The first wave took place in the aftermath of the two oil crises in the 1970s, but it was phased out in the early 1980s when oil prices started falling again. The second wave, which is also the focus of this paper, emerged in the early 1990s in response to increased concerns about climatic change (Nicolli & Vona, 2012). The adoption of these policies happened gradually over at least two phases. The first phase saw the adoption of RD&D (Research, Demonstration and Development) subsidies and grants. The second phase focused mainly on the use of market-based instruments (such as taxes, incentives, and tradable permits), which also resulted in policy diversification, since policies adopted early were kept in use jointly with new ones (Nicolli & Vona, 2012).

At a practical level, the proliferation of REP poses several challenges, one of them being the adoption of a uniform classification of all the different types of policy instruments

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that have been used to distinct and well defined categories. The absence of a common classification system can be problematic as it makes it difficult to compare findings from different studies that use different (ad-hoc) classifications.

Another important question for policy makers is about identifying the optimal policy mix that can be used to maximise the effectiveness of policy intervention in the energy sector – and in particular in innovation activity of renewable energy technologies (RET). On one hand, it can be argued that targeting a particular RET for support can help achieve a policy target more effectively. On the other hand, targeting specific RET can involve higher costs and greater scope for failures, not least because of possible interaction effects with other policies (Pitelis, 2018). Surprisingly to us, this question has not attracted as much attention in the context of the renewable energy sector, although more general variants of it have been at the centre academic debate in the literature on industrial policy and strategy – both of which items feature highly in the policy agenda of the UK government (Bailey et al., 2015).

In the context of this longstanding debate, it is arguable that more targeted policies are likely to involve a higher possibility of failure, both in identifying the target and in ensuring that targeting one type of technology does not have a negative repercussion on other technologies. Scholars have argued that targeting RE distorts the functioning of carbon markets and, therefore, hinders efforts to decarbonise the economy (Moselle & Moore, 2011; Less, 2012; Nordhaus, 2009). On the other hand, some scholars have argued that a policy mix that stresses the importance of specific technologies to foster RE innovation, alongside carbon pricing policies may be preferable (Stern, 2007; Grimaud & Lafforgue, 2008).

The aim of this paper is to determine the extent to which RET-specific policy instruments are more (or less) effective than RET-neutral ones, by evaluating their effectiveness in triggering innovation in the RE sector. To do this we adopt a common

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classification system of REP instruments, focusing on all key RET - namely *Biomass*, *Geothermal*, *Hydro*, *Solar*, and *Wind* energy technologies. We measure innovation activity for each of these technologies using patent statistics – a commonly used measure that has been adopted widely the innovation literature in general, and specifically in the modelling of innovation in the energy sector (Jaffe et al., 2000; Nelson, 2009)[1]. Our analysis uses a large sample of 21 OECD countries that are actively involved in the adoption of REP.[2]

The remainder of the paper is as follows: The next section provides an overview of the literature on the links between industrial policy and innovation in the energy sector and lays out the key hypotheses that we intent to test in this paper. Section three discusses our empirical methodology and also offers a discussion of our model specifications and key variables. Section four presents and discusses the results our analysis. Section five concludes.

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2. Research Background

The early 1990s witnessed a new wave of RE policies aimed at mitigating the impact of climate change. The United Nations Framework Convention on Climate Change triggered regular Conference of Parties (COP) meetings. A key meeting was COP3 (1997), where the Kyoto Protocol was adopted. By redirecting the innovation efforts of national governments towards

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[1] Although patent statistics are a common empirical approach, they have been criticised in terms of their efficacy in proxying innovation and for potential biases (Nelson, 2009), for their importance, their existing variation in the propensity to patent across countries and sectors, and their uncertainty in comparing information as a result of the differences in patent regimes for different countries (Johnstone, et al., 2008). Despite these limitations, a number of advantages of using patents as an innovation indicator are cited in the literature, such as the fact that patents are *granted for "*inventive technologies with commercial promise" (i.e. innovation) (Smith, 2004, p. 159), the availability of data, and their long history of records (the only innovation indicator extending back over centuries), and the classification of technologies into a detailed and slow-to-change system (Smith, 2004). A more detailed discussion of the merits and limitations of patents as a proxy of innovation intensity can be found in section three.

[2] These are the following: *Australia, Austria, Belgium, Canada, Finland, France, Germany, Ireland, Israel, Italy, Japan, Korea, Mexico, Netherlands, New Zealand, Norway, Spain, Sweden, Switzerland, United Kingdom, and the United States.*

RE the Kyoto protocol is widely believed to have helped increase the size of the global market for renewable energy and to have fostered interest in the research and development of such technologies . Despite recognition of the importance of RE policy, and the aforementioned diversification of RE policy instruments, there exists little agreement on a common classification of REP instruments.

In what follows, we put together a classification system of REP that draws upon earlier contributions on innovation by leading scholars in the field, such as Rosenberg (1974), Nelson (2009), and Nemet, (2009). In particular, our classification system distinguishes between three distinct types of policy instruments[3]:

- Technology-push policy instruments that foster technological change in RE from the supply side (the innovators), such as government-sponsored R&D and tax credits for companies to invest in R&D (Nemet, 2009). The theory suggests that, since such instruments depend on the exploitable “technological opportunities” and the “strength of science’’ in every sector (Rosenberg, 1974; Klevorick, et al., 1995; Nelson, 2009; Pitelis, 2018), firms need to develop their absorptive capacity to materialise opportunities emerging from advanced technologies (Rosenberg, 1990; Nemet, 2009; Pitelis, 2018) and are, therefore, viewed as complementary to demand-pull instruments (Nemet, 2009; Mazzucato, 2013).
- Demand-pull instruments that see demand as a driver of the rate and direction of innovation, arguing that demand factors both increase the market for and improve the

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[3] The classification of instruments was done by the authors, following the methodology proposed by Rogge and Reichardt (2016). More specifically, we allocate all policy instruments into one of three classes: technology-push, demand-pull, and systemic. The allocation of each policy instrument to a specific class was done by systematically reviewing the description of each individual policy and then using the rules and examples offered by Rogge and Reichardt (2016), and Groba & Breitschopf (2013) to characterise each policy instrument accordingly.

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incentive of firms to innovate. Examples of demand-pull instruments include tax credits and rebates for consumers of new technologies, as well as taxes on competing technologies.

- Systemic instruments that act at the level of the innovation system as a whole, instead of specific parts of it, and as a platform that facilitates the advantages of demand-pull and technology-push instruments. They also align the instrument mix to the needs of the actors involved and promote collaboration and knowledge transfer amongst market participants (Smiths & Kuhlmann, 2004). Examples include tax and subsidy reforms, infrastructure provision, and cooperative RD&D grants, among others (Rogge & Reichardt, 2016).

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The idea that environmental policy can help foster RE innovation is not new (see, for example, Porter & Van Der Linde, 1995). However, interest on these questions in the context of RE applications has flourished mostly over the last decade. Popp et al. (2009), for instance, found that both quota systems and demand subsidies may foster innovation by increasing the expected return from R&D investments. Johnstone et al. (2008), examined the extent to which RE policies foster RE innovation over the period of 1978–2003 and for 25 countries. They concluded that policy plays a significant role in determining patent applications, and that different types of policy instruments are effective for different RE sources. Nesta et al. (2014), examined the effect of various RE policies on innovation for different levels of competition and found that RE policies are more effective in forecasting green innovation in countries with deregulated energy markets. Their findings also showed that public support for RE is crucial for the generation of high-quality green patents, whereas competition enhances the production of green patents, regardless of their quality.

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Few studies have addressed the effects of specific REP on fostering innovation in RET. As an example of one of the earlier studies in the literature, Loitera & Norberg-Bohmb (1999) provide a comprehensive review of the history of the development and diffusion of wind power technologies in the United States. They found that demand-side policies are needed to encourage not only diffusion of wind energy but also innovation in the technology itself, and that weak demand-side policies risk severely limiting the effectiveness of research programs aimed at technological innovation. Wangler (2013), Peters et al. (2012), and, partly, Johnstone et al. (2008) (only for the case of tradable certificates), also found demand-pull instruments to have an important role in facilitating innovation activity.

Marques and Fuinhas (2012) examined the extent to which public policies towards RE are successful over the whole spectrum of RE technologies and concluded that incentive and subsidy policies (including feed-in tariffs – which are categorised as demand-pull policy instruments) and policy processes (systemic instruments) are significant determinants for the adoption of RE. Constantini et al. (2015) found that demand-pull policies are dominant (in the biofuel sector). They suggested that this is because other complementary technology-push supports are needed to increase the availability of scientific and technological capabilities and foster innovation. Palmer et al. (2015) examined the evolution of residential PV systems in Italy for 2006–2011 and found that the feed-in tariff scheme had, again, a positive effect on their rapid growth, beyond an initial stage (Palmer et al., 2015).

Lee and Lee (2013) explored patterns of innovation and evolution in energy technologies (including solar PV biomass, wind, tidal, and geothermal), particularly by focusing on similarities and differences across technologies. They concluded that customised policies are likely to be required for each technology. Hoppmann et al. (2013) conducted comparative case studies using a sample of nine global solar PV producers and concluded that demand-pull policies have a greater impact when they target more mature technologies.

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Dechezleprêtre and Matthieu (2014) analysed the influence of domestic and foreign demand-pull policies (e.g., guaranteed tariffs, investment, and production tax credits) in wind power across OECD countries on the rate of innovation in said technology. They concluded that wind technology improvements responded positively to policies, both at home and abroad.

Crespi et al. (2015) used data from Eurostat and the OECD to test empirically for the role of policy in inducing the adoption of environmental innovation by firms. They concluded that policies play a crucial role in either supporting or even spurring the adoption of environmental innovations. They also differentiated between (i) typologies of policy instruments and (ii) typologies of innovations and found that the inducement effects depend on the type of instrument under scrutiny. In this way, they provided empirical support linking inducement effects of a policy and the specific type of environmental innovation, since the latter reacted differently to the array of policy instruments scrutinised. Costantini et al. (2015) explored the differentiated impact of demand-pull and technology-push instruments in shaping technological patterns in the biofuels' sector. They concluded that demand-pull and technology-push factors are important drivers of innovation in the biofuels' sector.

Lindman and Söderholm (2016), analysed patent data for four western European countries over the period 1977–2009, with different model specifications, and found that both public R&D support (technology-push policy) and feed-in tariffs (demand-pull policy) have positively affected patent application counts in the wind power sector. In addition, they argued that the impact of feed-in tariffs became more profound as the technology matured, and the impact of public R&D support was greater if it was accompanied by feed-in tariffs. Nicolli and Vona (2016) studied the effect of REPs on innovation activity in different RETs for the EU countries and the years 1980–2007. They found that the inducement effect of REP is heterogeneous and more pronounced for wind generating technologies, which, for the period of their study, was the only technology that was sufficiently developed in terms of technology.

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In a broader sense, Grafström et al. (2017), who examined the technological patterns (i.e., invention, innovation, and diffusion) of the European wind energy sector, also found feed-in tariffs (demand-pull instruments) to be vital factors of said patterns (Grafström & Lindmand, 2017).

The current literature provides some, albeit limited, conclusions regarding which types of policy instruments work better, especially when it comes to targeting these instruments to achieve maximum return in innovation activity. The limitations of the conclusions result from the narrow focus of the studies, either in terms of the policy classification, the RET, and/or the countries examined. The policy classification adopted in this study allows for the examination of all policy instruments, and not only isolated policy instruments and it also enables us to distinguish between "general" policies and technology-specific policy instruments.

Based on the above, in this paper we test for the following two hypotheses.

***H_1*:** *Different types of RE policy instruments will have different effects on RE innovation*

and

***H_2*:** *RE policy instrument types that focus on specific RETs will have a stronger effect on RE innovation*

3. Methodology and Data Description

This study uses panel data drawn from 21 OECD countries, over the period 1990 to 2014. All of the countries in our sample have used and/or are currently using a range of policy instruments to support development of their RE sector. These also include some key members of the EU (*Austria, Belgium, Finland, France, Germany, Ireland, Italy, Netherlands, Norway, Spain, Sweden, Switzerland, United Kingdom)* widely perceived as leaders in the area of RE policy and innovation. We used year 1990 as starting point as this is when the second wave of RE

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policy adoption took place, while it also captures the effects before and after the adoption of Kyoto Protocol, which is said to have helped redirect innovative activities towards renewables (Rawlins & Allal, 2003). The year 2014 was chosen as the end date of our analysis due to data availability (see next section). Table 1 provides a summary of the definitions and source of the main variables.

[TABLE 1 ABOUT HERE]

Table 1: Definitions of main variables

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3.1 Measuring RE Innovation

In general, innovation can be measured both by means of input (such as R&D expenditure), and output (yield)-oriented activity, which, together, account for the results of the innovation process, such as patenting activity (Smith, 2004). In this paper, we have collected data for the latter.

Using patent statistics is a common and widely used way of measuring innovation activity; The use of patent statistics has been subject to some criticism in the past, questioning how unbiased these statistics are as a proxy for innovation (Nelson, 2009); their existing variation in the propensity to patent across countries and sectors, and their uncertainty in comparing information as a result of the differences in patent regimes for different countries (Johnstone, et al., 2008). Despite this criticism and limitations, patent data are still the most commonly-used determinant of innovation, and the one that this study uses to model innovation outcomes.

There are a number of reasons why we choose to proxy innovation by using this metric. First, patents are *granted for* "inventive technologies with commercial promise" (Smith 2004, p. 159), which is the type of innovation we wish focus on these paper. Although this paper is

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an example of research effort on renewable technologies, we would not want to have included in our dataset – as our focus is on commercial applications of such technologies. Also, the availability of data, the long history of patent records (the only innovation indicator extending back over centuries), and the classification of technologies into a detailed and slow-to-change system (Smith, 2004) renders patents data a very good proxy for the type of innovation that we wish to study here.

More specifically, in this paper we source patent data from the European Worldwide Patent Statistical Office (EPO) database. In line with the extant literature (Johnstone, et al., 2008; Nesta, et al., 2014) the International Patent Classification system was used, because it allows us to distinguish between inventions across different RE technological fields in Biomass, Geothermal, Hydro, Solar, and Wind. PCT patent applications in the international phase were considered, and filed directly at the International Bureau of the World Intellectual Property Organisation. The patents were assigned to a country on the basis of the address of the inventor. In cases where there were more than one assigned inventors' addresses, one patent was attributed to each country. Overall, 198,305 patent counts were obtained.

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3.2 RE policies and REP Instruments

We obtained data on RE policies from the International Energy Agency (IEA) database for the period 1990-2014. Policies can target one or more RETs, as well as one or more RE sector(s). For example, in 2000 the UK introduced the Renewable Energy Obligation, which targeted all RETs and was applicable across all sectors (e.g. electricity, heating and cooling, and transport). In the same year, the UK also introduced the Energy Crops Scheme, which targeted only biomass related technologies, and was only relevant to sectors related to power and heat. In a similar manner, in 1990 Germany introduced the Environment and Energy Saving Programme which provided loans specifically for onshore and offshore wind technologies, for biomass technologies related to power, heat, and transportation, and for solar technologies related to the heating sector. However, Germany's Integrated Climate Change and Energy Programme (2007) targeted all RETs across all sectors. For this paper, we have collected data on RE policy instruments that target only the electricity sector and five RET. The following figure summarises the total patent applications per year for all countries under examination, alongside the total policy instruments per year for all countries.

[FIGURE 1 ABOUT HERE]

Figure 1: Total patent applications and total policy instruments used per year (all countries)

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The data on RE policy instruments were divided to two categories, those targeting multiple RETs, and those targeting one specific RET. They were also classified into technology-push, demand-pull, and systemic, by thoroughly reviewing the specifics of each individual policy. Policy descriptions were usually provided in the IEA database, and in the few cases where it was not, other literature was consulted – mainly the original policy documents. It should be noted that some policy instruments fell into more than one type, i.e. being both technology-push and demand-pull4. In such cases, a count was attributed to both. The summary of all instruments related a specific RET, is summarised in Table 2, while Table 3 summarises the instruments per RET and per type (technology-push (TP), demand-pull (DP), and systemic (sys)).

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[4] For example, France had at the period under examination 3 Demand-pull and Systemic instruments; and 3 Technology-push and Systemic instruments. Germany had 1 Demand-pull and Systemic; 1 Technology-push and Systemic; and 1 Technology-push and Demand-pull. Italy had 6 Demand-pull and Systemic; and 1 Technology-push and Demand-pull. Luxembourg had 3 Demand-pull and Systemic; and 4 Technology-push and Demand-pull instruments; and finally, the United Kingdom had 7 Demand-pull and Systemic; 1 Technology-push and Demand-pull; and 3 Technology-push and Systemic instruments.

[TABLE 2 AND 3 ABOUT HERE]

Table 2: Number of policy instruments used by Country and RET (1990-2014)

Table 3: Distribution of used policy instruments by category and country (1990-2014)

3.3 Control Variables

Inducing green innovation is not just a matter of public policy. A number of studies on innovation determinants of green technologies find that market-specific characteristics, such as market size, can be important influences in the decision process of firms on how to allocate their R&D activities between countries (see, for instance, Noailly and Ryfisch (2015); Corrocher and Solito, 2017; Arfi et al. 2018; among several others). To capture this effect, all of our estimated equations include a control for market size. Data on household and industry sector electricity consumption were obtained from the IEA/OECD Database, in GWh. Both observed and calculated balances exist; in this paper, these are averaged.

We have also included a newly developed index by the OECD related to the market share of the largest generator in the electricity market. We expect that this should have a negative effect on RE innovation, as the higher a firm's market share, the less incentive it may have to innovate (Sandulli et al., 2012). Data were obtained for most countries from the Eurostat database. As in Nesta et al. (2014), we have used a dummy variable to pick up any effects of the Kyoto protocol, which came into effect in 2005.

We have also introduced a new indicator, that of "renewable energy innovation intensity", which is the ratio of individual RET patenting activity over the total RET patenting

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activity. Finally, to remove the country-specific time invariant components from the error term, country dummies have been used in the form of fixed effects. A vector of year dummies (u) was also used pick up time effects (trend).

3.4 Methodology

Count data is most commonly modelled with the use of Poisson or Negative Binomial (NB) estimators. Poisson models, however, are known to be prone to bias when the dependent variable is over-dispersed (which is commonly measured by taking the relative value of the variance to the mean after accounting for the effect of all predictors). This can be overcome by using the NB Regression Model (NBRM), which introduces unobserved heterogeneity across the Poisson means (Costantini et al., 2015). In all cases, the variance of our dependent variables was found to be larger than the mean, implying over-dispersion – making NBRM an ideal candidate for the modelling of this data. We use three different models and specifications to assess our two hypotheses, as described below.

Model 1 examines the total RE Innovation per year per country as being equal to the three types of RE policy instruments; i.e.; the effects of technology-push, demand-pull, and systemic instruments on the overall RE innovation activity. A standard fixed effects model setting was considered, in the following form:

$$\sum RE\ Innovation_{i,\,t} = \beta_1(\sum REP\ Tech.\ Push_{i,t}) + \beta_2(\sum REP\ Dem.\ Pull_{i,t}) + \beta_3(\sum REP\ Systemic_{i,t}) + \beta_4(Market\ Share_{i,t}) + \beta_5(Kyoto_{i,t}) + \beta_6(Electricity\ Consumption_{i,t}) + \beta_7 (RE\ Inn.\ Intensity_{i,t,Te}) + v_i + u_t + \varepsilon_{i,t} \qquad (1)$$

where, *i = values per country,* and *t = year (1990, …, 2014), and v and u are vectors of country and time dummies, respectively.*

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Model 2 examines the effects of the three types of RE policy instruments on RE innovation on the multiple level, i.e. those policies that target more than one technology, but not necessarily all of them. RE patent counts per RET is our DV, and the sum of policy instrument per type and per technology is our IV. A standard model setting is again considered, in the following form:

$$RE\ Innovation_{i,\,t,Te} = \beta_1(M.\,Tech\ Push_{i,t,Te}) + \beta_2(M.\,Dem\ Pull_{i,t,Te}) + \beta_3(M.\,Systemic_{i,t,Te}) + \beta_4 (Market\ Share_{i,t,Te}) + \beta_5(Kyoto_{i,t,Te}) + \beta_6(Electricity\ Consumption_{i,t,Te}) + \beta_7 (RE\ Inn.\,Intensity_{i,t,Te}) + v_i + u_t + \varepsilon_{i,t,Te} \tag{2}$$

where, i = values per country, t = year (1990, …, 2014), Te = type of technology (Biomass, Geothermal, Hydro, Solar and Wind) and u are vectors of country and time dummies, respectively, and Te=Technology. M implies “multiple” – i.e. a policy that targets simultaneously more than one technologies.

Model 3 examines the effects of the three types of RE policy instruments on RE innovation when targeting one specific RET. RE patent counts per RET is our DV, and the sum of policy instruments per type and per technology is our IV. A standard model setting is again considered, in the following form:

$$RE\ Innovation_{i,\,t,Te} = \beta_1(Tech\ Push_{i,t,Te}) + \beta_2(Dem\ Pull_{i,t,Te}) + \beta_3(Systemic_{i,t,Te}) + \beta_4 (Market\ Share_{i,t,Te}) + \beta_5(Kyoto_{i,t,Te}) + \beta_6(Electricity\ Consumption_{i,t,Te}) + \beta_7 (RE\ Inn.\,Intensity_{i,t,Te}) + v_i + u_t + \varepsilon_{i,t,Te} \tag{3}$$

where, i = values per country, t = year (1990, …, 2014), Te = type of technology (Biomass, Geothermal, Hydro, Solar and Wind) and u are vectors of country and time dummies, respectively, and Te=Technology.

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4. Empirical Results and Discussion

In this section we present and discuss the results of our empirical estimations. A summary of these results can be found in Tables 4 and 5.

[TABLE 4 ABOUT HERE]

Table 1: Negative binomial regression estimates for the effect of policy instruments on innovation: Equations (1) and (2)

More specifically, table 4 shows the results of our estimation for the effect of different policy instruments on innovation activity (equation 1), first for all technologies (column 2) and then by type of technology (columns 3-6). Overall, these results show that RE policy has been mostly successful in influencing innovation activity of RET over our sample period - although the magnitude, sign and level of statistical significance of these effects varies by policy instrument and type of technology. It is interesting to note that the technology-push instruments have had a weak effect on the overall RE innovation, a result that has also been reported in other parts of the literature (Pitelis, 2018; Nemet, 2009; Rosenburgh, 1979).

Demand-pull policies, on the other hand are found to have a positive and highly significant effect on RE innovation. Systemic policy instruments are shown to have a significant but negative effect on RE innovation. The intuition of this effect becomes clear, if one considers the auxiliary nature and purposes of such policy instruments – which are primarily used to support and align the an existing mix of demand pull and/or technology-push policies (Smiths & Kuhlmann, 2004). The same result keeps reappearing in all of our estimations bar one specification of equation (2) (solar); and across all three models that we

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consider in this study. Demand-pull are the only type of policy instruments that are found consistently to have a positive and significant effect on innovation in one form or another, across all types of RET.

In terms of control variables, market share was found to be negative and significant (at the 1% level), indicating that higher market concentration is likely to reduce the effectiveness of policy intervention in stimulating innovation, since there will be less of an incentive for the larger firms to purse differentiation strategies (Sandulli et al., 2012). In such markets, electricity suppliers are more likely to use consumer-facing strategies to increase their market share (Rutter et al., 2017).

The dummy variable that was used to proxy the Kyoto protocol effect was found to be positive and significant, suggesting that RE patenting activity can be influenced by constraints and incentives provided by international accords and that the Kyoto protocol has, indeed, had a noticeable impact. Finally, and in line with intuition, electricity consumption was found to be positive and significant, suggesting that RE innovations are more likely to take place when there is a market for them.

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4.1 Effectiveness of multi-RET policy intervention on individual types of RET

The last five columns of table 4 show the estimation results for equation (2) – which is used to evaluate the effectiveness of policy intervention for individual RET, using policy instruments that target more than one RET at the same time. Overall the estimated sign and magnitude of the coefficients is generally in line with intuition and in agreement with the results that have been reported previously in the literature. In most of the specifications that we tried, the coefficients remained overall highly significant – although there were differences between different types of technologies. These differences are discussed in greater detail in the remainder of this section.

Starting with biomass, our results show that technology-push instruments have had an insignificant effect on fostering innovative activity. That result holds true for policy instruments that target multiple RETs; as well as for those policies that focus on biomass only. Similar to the earlier results for equation (1), demand-pull policy instruments are again found to have had a positive and significant effect. However, this time we also find that policies that targeted multiple RETs had a more significant and larger effect in stimulating innovation activity in Biomass technologies, than policies that were aimed exclusively at biomass technologies (table 2, specification 1).

It is also worth noticing that market share and the Kyoto protocol controls do not have an impact on the biomass innovative activity. In the case of market share, this can be because biomass belongs to the first-generation, already mature technologies (IEA, 2006). Essentially, technologies for power generation from solid biomass are very similar to those that are used widely for coal. Biomass very often has been used either in coal and biomass co-firing power stations or in retired coal-fired stations that were converted to biomass only. Therefore, some of the largest biomass facilities are, in fact, operated by market incumbents who have previously burnt coal.

Similarly, market share has had no effect on the innovative activity of geothermal technologies. As in the case of biomass technologies, geothermal is also a first-generation technology that has reached maturity by using tried and tested turbine systems. The Kyoto protocol and energy consumption variables are found to be positive and significant in both model specifications at 1%.

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In the case of hydro technologies, both technology-push and demand-pull instruments are found to have a positive and significant effect on innovation activity. Systemic instruments, on the other hand, are shown to have negative and highly significant effect on the innovation activity for this type of RET. Both technology-push and demand-pull instruments for wind technologies are found to have a positive and significant effect on innovation activity.

4.2 Effectiveness of RET-specific policy intervention on individual types of RET

Finally, we turn our attention to table 5, which shows the estimated coefficients for equation (3). Contrary to the specifications that were discussed in table 4, this set of estimations evaluates the effectiveness of policy intervention for an individual RET using instruments that target only one type of RET (as opposed to multiple). Our results show that, as policy instruments become more targeted to individual technologies, some of the effects that we described in earlier parts of this section change.

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[TABLE 5 ABOUT HERE]

Table 5: Negative binomial regression estimates for the effect of policy instruments on innovation: Equation (3)

Starting with hydro technologies, we find that the use of hydro-specific policy instruments weakens the effectiveness of technology-push and systemic policies, which are now shown to have non-statistically significant effect on innovation activity. A similar result is found for wind technologies, where again the use of wind-specific policy instruments results in rendering technology-push policies less effective than in previous estimations. Unlike hydro technologies, the effect of wind-specific systemic instruments is found to be negative and significant at the 5% level.

Moreover, energy consumption and market share have a positive and strongly significant effect on innovation activity for both wind and hydro technologies. The Kyoto protocol was found to have a significant effect only in the case of wind technologies. This is because for most regions, deployment of hydroelectric technologies is heavily reliant on topological characteristics. Wind energy, on the other hand, is a challenger technology that removes incumbent market share (Green & Vasilakos, 2011) and has benefitted greatly from the advancement of the climate change agenda.

It should be noted that solar is completely different from the rest of the technologies examined above, in terms of the effect that policy intervention has on the innovation activity of this type of RET. When in table 4 we considered the effect of multi-technology policy instruments on innovation for this type of RET, we found no significant effect for this type of technology. However, this result changes when more targeted policy instruments are used. Indeed, as in can be seen in table 5 (specification 4), solar-specific demand-pull instruments have had a positive and highly significant effect on the innovation activity of these technologies. This result highlights how differences in the intrinsic design of RE policy instruments may have a significant effect on the effectiveness of each type of technology.

5. Concluding Remarks

In this paper we examined the effectiveness of different types of renewable energy (RE) policies in fostering innovation across an array of renewable energy technologies, namely biomass, geothermal, hydro, solar and wind. Using a rich dataset of 21countries and 24 years, we identified all renewable energy policies that were used in each one of these countries and

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categorised them according to their properties to one of three distinct policy types: technology-push, demand-pull, and systemic policy instruments. We then analysed the effects of policy intervention, by policy instrument and generating technology. Our results show very clearly that one size does not fit all. The effectiveness of policy intervention often depends on the specific characteristic of each type of technology. Innovation activity of some technologies is found to be more responsive to demand-pull policy instruments only (e.g. geothermal), whereas for other technologies a more mixed approach maybe more effective (e.g. wind). And sometimes policies that focus on only technology are more effective in stimulating than multi-technology ones (e.g. solar).

Our research adds to the renewable innovation literature in several ways. We provide a clear classification that can be used to distinguish between the three different types of policy instruments that we consider in this study. This classification is built on strong theoretical foundations (such as Rosenberg, 1974; Nemet, 2009), and its has been discussed and commended in number of theoretical papers (such as Rogge & Reichardt, 2016; Pitelis, 2018).

The results that we present in this paper show clearly that differences between policy instruments (and how they are used) matter and should not be overlooked. Aggregating across policy types may mask important differences in terms of effectiveness and misinform the design of energy policy. Our results highlight these differences: Demand-pull policy instruments were found to have a positive and significant effect on innovation in all cases, except for solar energy technologies. Technology-push instruments were significant only for the cases of hydro and wind energy technologies, whereas systemic instruments were found to be significant for the cases of biomass, hydro, and wind energy technologies but negative everywhere else. Our last set of estimations (table 5) also showed that, when it comes to targeting one specific technology, only demand-pull policies seem to be effective – something that was also true for the case of solar energy technologies.

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In terms of policy recommendations, it is apparent that different technologies require different types of policy instruments to foster innovation. Our results suggest that demand-pull policies are likely to be more effective in fostering innovation in renewable energy technologies when compared to other alternatives. Policy makers should take note of these findings when designing their energy innovation policy and focus on deploying these policy instruments that are shown to be the most effective for each type of technology.

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Table 1: Definitions and description of main variables

Name	Definition	Notes	Source

Patents	Total patent counts filed per country per year, filed under the PCT	Data were collected using International Patent Classification, for Bioenergy; Geothermal; Hydroelectricity; Ocean Energy; Solar Energy; Wind Energy	PATSTAT (European Patent Office)
Policy Instruments	The IEA/IRENA Global Renewable Energy Policies and Measures Database provides information on policies and measures taken or planned to encourage the uptake of renewable energy in all IEA and IRENA Member countries and signatories.	OECD Countries; All Policy Types; All RE Policy Target; Only Electricity Sector; Effective between 1974-2015; All Jurisdictions; All Policy Statuses; Large and Small Plant Sizes	IEA/IRENA Joint Policies and Measures Database
Market Share	Market share of the largest generator in the electricity market	Data exist for most countries and from 1999 to 2015	Eurostat
Kyoto Protocol	The Kyoto Protocol is an international agreement linked to the United Nations Framework Convention on Climate Change, which commits its Parties by setting internationally binding emission reduction targets. The Kyoto Protocol was adopted in Kyoto, Japan, in 1997 and entered into force in 2005.	0 for all years prior to 2005; 1 for the following ones	Authors
Electricity Consumption	The IEA Electricity Information: OECD Electricity and Heat Supply and Consumption (GWh, TJ) database provides electricity and heat balance data for 35 OECD countries	Data were collected for EU15 member states. Both observed and calculated balances were collected and averaged.	IEA/OECD

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Table 2: Number of policy instruments used by country and RET (1990-2014)

Country	Biomass Instruments	Geothermal Instruments	Hydro Instruments	Solar Instruments	Wind Instruments
Australia	90	79	73	126	85
Austria	27	27	8	28	27
Belgium	56	56	56	56	80
Canada	41	32	48	46	41
Finland	26	10	21	10	39
France	44	34	37	34	34
Germany	53	53	53	21	59
Ireland	17	7	24	14	24
Israël	19	19	19	31	25
Italy	38	37	37	37	37
Japan	11	11	11	23	11
Korea	32	21	21	32	32
Mexico	41	56	59	76	55
Netherlands	19	9	9	25	15
New Zealand	3	3	3	3	3
Norway	9	9	21	9	19
Spain	50	50	44	73	83
Sweden	21	14	21	23	29
Switzerland	12	12	12	12	12
United Kingdom	104	90	95	103	112
United States	136	134	121	215	191

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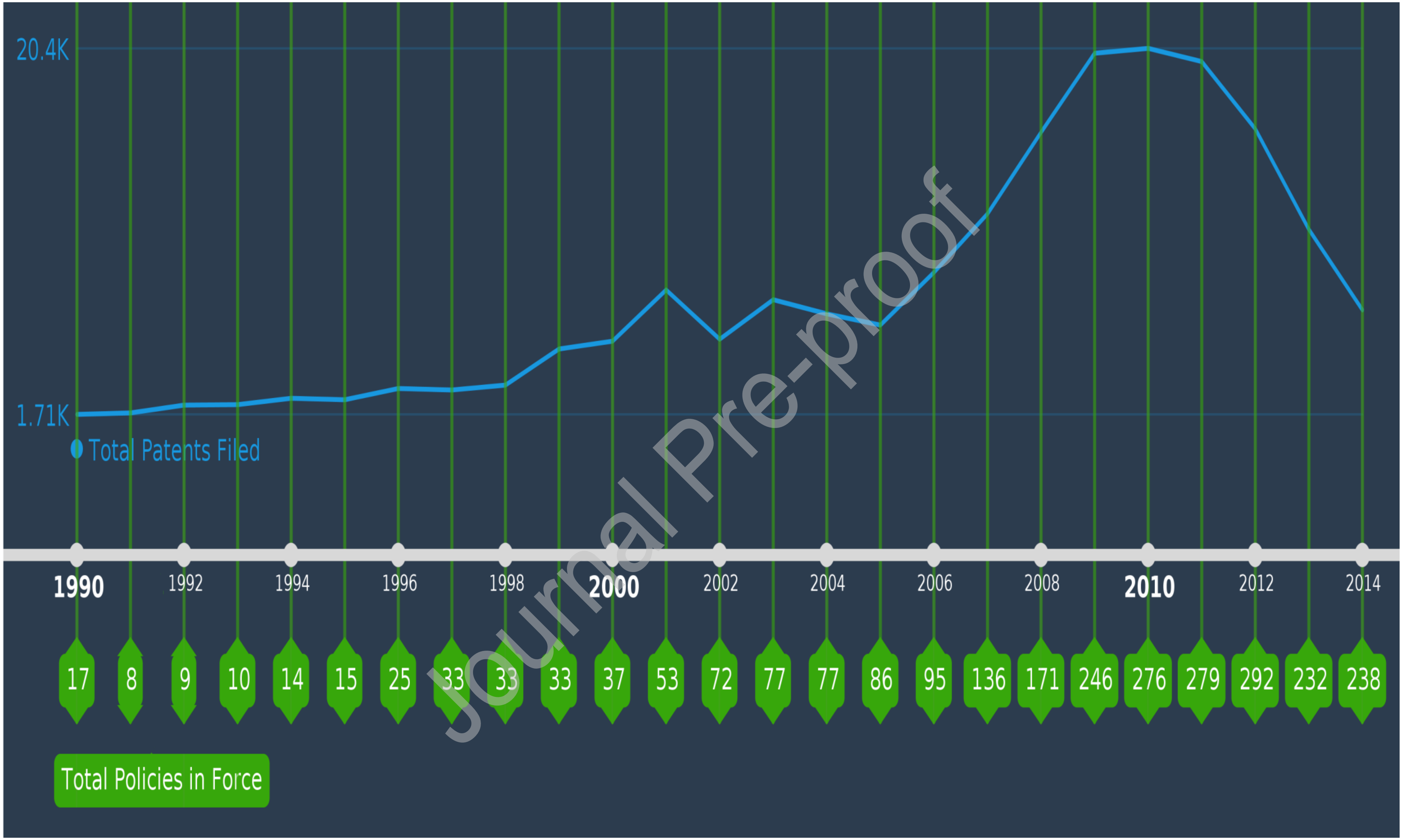

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Figure 2: Total patent applications and total policy instruments used per year (whole sample)

Table 3: Distribution of policy instruments by category and country (1990-2014)

	Biomass			**Geothermal**			**Hydro**			**Solar**			**Wind**		
Country	**TP**	**DP**	**Sys**	**TP**	**DP**	**Sys**	**TP**	**DP**	**Sys**	**TP**	**DP**	**Sys**	**TP**	**DP**	**Sys**
Australia	25	32	33	30	18	31	21	30	22	39	54	33	21	40	24
Austria	7	15	5	7	15	5	0	3	5	8	15	5	7	15	5
Belgium	0	17	39	0	17	39	0	17	39	0	17	39	0	29	51
Canada	25	16	0	30	2	0	32	16	0	30	16	0	25	16	0
Finland	11	5	10	0	0	10	11	0	10	0	0	10	11	5	23
France	20	19	5	20	9	5	20	8	9	20	9	5	20	9	5
Germany	19	7	27	19	7	27	19	7	27	0	13	8	44	7	8
Ireland	2	10	5	2	0	5	9	10	5	9	0	5	9	10	5
Israël	11	0	8	11	0	8	11	0	8	11	6	14	11	6	8
Italy	1	16	21	0	16	21	0	16	21	1	20	16	0	16	21
Japan	0	3	8	0	3	8	0	3	8	6	6	11	0	3	8
Korea	11	14	7	11	3	7	0	14	7	11	14	7	11	14	7
Mexico	1	11	29	1	18	37	1	18	40	13	22	41	1	18	36
Netherlands	0	14	5	0	4	5	0	4	5	3	10	12	0	4	11
New Zealand	0	0	3	0	0	3	0	0	3	0	0	3	0	0	3
Norway	0	3	6	0	3	6	0	15	6	0	3	6	5	3	11
Spain	6	10	34	6	10	34	6	10	28	7	20	46	11	20	52
Sweden	7	3	11	0	3	11	7	3	11	6	6	11	11	7	11
Switzerland	0	6	6	0	6	6	0	6	6	0	6	6	0	6	6
United Kingdom	13	44	47	4	39	47	4	44	47	12	44	47	7	56	49
United States	58	47	31	58	45	31	44	52	25	93	70	52	79	59	53

Note: TP = Technology-push; DP = Demand-pull; Sys = Systemic

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Table 2: Negative binomial regression estimates for the effect of policy instruments on innovation: Equations (1) and (2)

	Equation 1	**Equation 2**				
		Specification				
		(1)	**(2)**	**(3)**	**(4)**	**(5)**
	Total RE Patents	**Biomass Patents**	**Geothermal Patents**	**Hydro Patents**	**Solar Patents**	**Wind Patents**
Total Technology-Push Instruments	0.0153 (-0.58)					
Total Demand-Pull Instruments	0.113*** (-6.71)					
Total Systemic Instruments	-0.0316* (-2.00)					
Multiple Technology-Push Instruments (Biomass)		0.212 (-1.73)				
Multiple Demand-Pull Instruments (Biomass)		0.236** (-2.88)				
Multiple Systemic Instruments (Biomass)		-0.151* (-1.99)				
RE Innovation Intensity (Biomass)		3.931*** (-10.78)				
Multiple Technology-Push Instruments (Geothermal)			0.361 (-1.6)			
Multiple Demand-Pull Instruments (Geothermal)			0.399** (-2.91)			
Multiple Systemic Instruments (Geothermal)			-0.138 (-1.68)			
RE Innovation Intensity (Geothermal)			18.38*** (-11.19)			
Multiple Technology-Push Instruments (Hydro)				0.265* (-2.43)		

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Multiple Demand-Pull Instruments (Hydro)				0.410*** (-4.62)		
Multiple Systemic Instruments (Hydro)				-0.122* (-2.11)		
RE Innovation Intensity (Hydro)				2.441*** (-7.35)		
Multiple Technology-Push Instruments (Solar)					0.167 (-1.83)	
Multiple Demand-Pull Instruments (Solar)					0.145 (-1.92)	
Multiple Systemic Instruments (Solar)					-0.0535 (-1.34)	
RE Innovation Intensity (Solar)					3.038*** (-9.92)	
Multiple Technology-Push Instruments (Wind)						0.221** (-2.6)
Multiple Demand-Pull Instruments (Wind)						0.326*** (-5.2)
Multiple Systemic Instruments (Wind)						-0.181*** (-4.19)
RE Innovation Intensity (Wind)						3.459*** (-12.02)
Market Share	-0.0109*** (-3.32)	-0.00599 (-1.33)	-0.00302 (-0.52)	-0.00883** (-2.62)	-0.0177*** (-4.51)	-0.00866* (-2.40)
Kyoto Protocol Dummy	0.175* (-2.1)	-0.0587 (-0.46)	0.670*** (-4.35)	0.158 -1.69	0.443*** (-4.01)	0.343*** (-3.99)
Electricity Consumption	0.00000325*** (-4.74)	0.00000575*** (-7.8)	0.00000578*** (-5.75)	0.00000439*** (-6.46)	0.00000302*** (-3.86)	0.00000232** (-2.75)

Reported figures are coefficients (β) for negative binomial regression estimates. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

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Table 5: Negative binomial regression estimates for the effect of policy instruments on innovation: Equation (3)

Model 3					
	Specification				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
	Biomass Patents	**Geothermal Patents**	**Hydro Patents**	**Solar Patents**	**Wind Patents**
Technology-Push Instruments (Biomass only)	0.315 (-1.9)				
Demand-Pull Instruments (Biomass only)	0.179* (-2.19)				
Systemic Instruments (Biomass only)	-0.224 (-1.27)				
RE Innovation Intensity (Biomass)	3.861*** (-10.64)				
Technology-Push Instruments (Geothermal only)		0.574 (-1.85)			
Demand-Pull Instruments (Geothermal only)		0.421** (-2.94)			
Systemic Instruments (Geothermal only)		-0.122 (-0.68)			
RE Innovation Intensity (Geothermal)		18.90*** (-11.65)			
Technology-Push Instruments (Hydro only)			0.115 (-0.77)		
Demand-Pull Instruments (Hydro only)			0.530*** (-5.5)		

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Systemic Instruments (Hydro only)			-0.0916 (-0.76)		
RE Innovation Intensity (Hydro)			2.456*** (-7.44)		
Technology-Push Instruments (Solar only)				0.145 (-1.26)	
Demand-Pull Instruments (Solar only)				0.242** (-2.86)	
Systemic Instruments (Solar only)				-0.1 (-1.35)	
RE Innovation Intensity (Solar)				2.951*** (-9.79)	
Technology-Push Instruments (Wind only)					0.121 (-1.21)
Demand-Pull Instruments (Wind only)					0.376*** (-5.81)
Systemic Instruments (Wind only)					-0.154* (-2.31)
RE Innovation Intensity (Wind)					3.245*** (-11.48)
Market Share	-0.00481 (-1.02)	-0.00244 (-0.44)	-0.00977** (-2.78)	-0.0169*** (-4.21)	-0.00868* (-2.41)
Kyoto Protocol Dummy	-0.0488 (-0.38)	0.651*** (-4.46)	0.108 (-1.17)	0.393*** (-3.57)	0.232** (-2.63)
Electricity Consumption	0.00000589*** (-7.86)	0.00000599*** (-6.43)	0.00000466*** (-6.55)	0.00000312*** (-3.98)	0.00000302*** (-3.51)

Reported figures are coefficients (β) for negative binomial regression estimates. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

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Declaration of interest

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

On behalf of all authors, I confirm that there are no conflicts of interest of any kind to disclose.

Kind regards,

Nicholas Vasilakos
(on behalf of Alkis Pitelis, Nicholas Vasilakos and Konstantinos Chalvatzis)
University of East Anglia

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Highlights:

- We assess effectiveness of innovation policies by policy instrument and technology.
- three policy types are considered: technology-push, demand-pull, and systemic
- demand-pull policies are more effective than any other type of policy intervention

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