International Entrepreneurship Review

2024, Vol. 10, No. 1

10.15678/IER.2024.1001.05

Does environmental policy stringency matter for eco-innovation? Evidence from the EU countries

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ABSTRACT

Objective: The objective of the article is to examine the influence of environmental policy stringency on the eco-innovation level, measured by a number of patents, in European Union countries.

Research Design & Methods: The research method was quantitative. The study used ordinary least squares (OLS) panel regression analysis based on data covering 18 EU countries (Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, the Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, and Sweden) and a period from 2013 to 2020 (144 observations). In estimated models, gross domestic product per capita, material import dependency, and human resources in science and technology served as control variables. The Organization for Economic Co-operation and Development, the European Innovation Scoreboard, Eurostat, and the World Bank were the data sources.

Findings: Higher stringency of technology support and market-based instruments positively influences eco-innovation-related patents in EU countries whereas more strict non-market-based instruments do not impact the eco-innovation level. Technology support instruments are more effective in stimulating eco-innovation than market-based instruments. Individual technology support instruments differ in their impact on eco-innovation with R&D subsidies being the most important. The stringency of feed-in tariffs and auctions is a significant factor triggering eco-innovation in the case of wind energy technologies, but not in the case of solar ones.

Implications & Recommendations: This study suggests that stringent technology support and market-based instruments are effective in stimulating eco-innovation in EU countries considered in the research sample. The environmental policy aimed at fostering eco-innovation should concentrate on increasing R&D subsidies for clean technologies. Further tightening emission standards aiming to enhance eco-innovation level is not recommended.

Contribution & Value Added: This study contributes to the literature on the importance of environmental policy stringency in fostering eco-innovation and provides new empirical evidence by examining not only instruments that may have an indirect impact on eco-innovation (i.e. market and non-market ones) but also technology support instruments, which have received less attention in previous studies. The analysis used data on the recently updated and improved OECD environmental policy stringency index.

Article type:	research article
Keywords:	environmental policy stringency; eco-innovation; technology support instruments; R&D subsidies; environmental taxes; environmental standards
JEL codes:	O38, Q58

Received: 16 September 2023 Revised: 20 December 2023 Accepted: 21 December 2023

Suggested citation:

Godawska, J. (2024). Does environmental policy stringency matter for eco-innovation? Evidence from the EU countries. *International Entrepreneurship Review,* 10(1), 69-82. https://doi.org/10.15678/IER.2024.1001.05

INTRODUCTION

Eco-innovation, also known as 'environmental,' 'green' or 'ecological' innovation, can be defined as the introduction of any new or significantly improved product, process, organizational change or marketing solution that decreases negative impacts or enhances positive influence on the environment throughout its life cycle (Tomala & Urbaniec, 2021, p. 71). Eco-innovation has been crucial to achieving sustainable development goals, as evidenced by, for example, the catalytic converter already used in vehicles to reduce the emission of gaseous pollutants and by the current need to replace non-renewable energy sources with others that are competitive in terms of cost and conditions of use.

The determinants of undertaking eco-innovations by companies are of increasing interest to researchers and policymakers (especially in the European Union) due to their role in reducing the negative environmental footprint and increasing firms' competitiveness. In general, these determinants can be divided into internal factors, related to the resources, capabilities and competences of companies, and external factors such as public policies, market conditions, and society's environmental awareness. Internal factors include among others firm's environmental strategy, internal R&D activities, own financing resources, commitment to green supply chains, and an eco-innovation-friendly corporate culture (Rehfeld *et al.*, 2007; Kiefer *et al.*, 2019; Keshminder & del Rio, 2019). External factors refer to the influence of various stakeholders on enterprises' decision to eco-innovate, including the government (regulation, subsidies), consumers (demand for green products) or capital providers (access to external financial sources) as well as to the collaboration with universities and other partners enabling the acquisition of knowledge necessary for the development of environmental innovations (Alzakri, 2023; Bolivar-Ramos, 2023).

The state's environmental policy is considered to be a particularly important external factor in the context of stimulating eco-innovation (Horbach *et al.*, 2013; Fusillo *et al.*, 2019; Biscione *et al.*, 2021; D'Amato *et al.*, 2021). It can be assumed that the more restrictive the environmental policy (*i.e.* the more costly environmentally harmful activities for companies or the greater the scale of support for environmentally friendly activities from public funds), the greater the companies' tendency to be eco-innovative. The effect of environmental policy on inducing eco-innovation may be indirect and consists in encouraging firms to search for more effective solutions that allow them to meet the requirements of environmental policy at a lower cost. Moreover, tightening environmental policy can lead to the increase in the ecological awareness of society and in consequence consumer pressure may make firms implement eco-innovation. The direct effect of stringent environmental policy is related to one type of its instruments, *i.e.* technology support ones, and consists in subsidizing R&D on environmental technologies and in price support for the adoption of specific technologies (*e.g.* based on renewable energy sources), desirable from the perspective of environmental policy goals. In the latter case, stimulating innovation may result from learning by doing, *i.e.* generating knowledge through the production and usage of technology (Johnstone *et al.*, 2012; Palage *et al.*, 2019).

The purpose of this study was to examine the influence of environmental policy stringency on the eco-innovation level, measured by number of patents, in 18 European Union countries over the 2013-2020 period. Considering different levels of stringency of environmental policy (policy as a whole, main types of instruments and individual instruments aimed at supporting technology), I formulated the following research questions:

RQ1: Does the overall environmental policy stringency impact the eco-innovation level?

RQ2: Which type of environmental policy instruments (market-based, non-market-based or technology support) stimulate eco-innovation the most taking into account their stringency?

RQ3: Which technology support instruments (subsidies for R&D, feed-in tariffs and auctions for solar and wind energy) stimulate eco-innovation the most considering their stringency?

This study contributes to the existing empirical literature on the significance of environmental policy stringency in fostering eco-innovation twofold. Firstly, the analysis included both instruments that may have an indirect impact on eco-innovation (*i.e.* market-based and non-market-based ones) and technology support instruments. Previous studies examined the impact of environmental stringency on eco-innovation focusing mainly on market-based and non-market-based instruments, paying less attention to technology support instruments. Secondly, the analysis used data on the recently updated and upgraded index of environmental policy stringency developed by the OECD, which allows for a longer research period than before (up to 2020 instead of 2015).

The rest of the article is organized as follows. Firstly, I will discuss the relevant literature on the relationship between environmental policy stringency and the eco-innovation. Next, I will present the variables, data, and methodology. The following section will report the results of the econometric analysis performed and discuss them. The final section will provide conclusions, research limitations, and recommendations for policymakers and future studies.

LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

The environmental policy has been identified as a crucial driver for eco-innovation (Horbach *et al.*, 2013; Fusillo *et al.*, 2019, Biscione *et al.*, 2021). Nowadays, a very wide range of different environmental policy instruments is used as a tool to support sustainable development in most countries around the world. These instruments include three main types: market-based, non-market-based, and technology support ones. Market-based instruments such as environmental taxes and tradeable emissions rights put a price on environmentally harmful activities (*e.g.* emitting pollution) and motivate companies to diminish their impact on the environment in order to achieve cost savings. Non-market-based instruments – also called 'command-and-control' regulations – include emission limits, technology- and performance-based standards. Companies are obliged to comply with them and any violation is in principle punished. Technology support instruments aim to create stimuli for the development of environmental technology through R&D (subsidies) and the adoption of desired technologies (*e.g.* feed-in tariffs for solar energy production).

The environmental policies in various countries and over time differ in terms of stringency, *i.e.* 'the strength of the environmental policy signal – the explicit or implicit cost of environmentally harmful behaviour, for example, pollution' (OECD, 2016, p. 3). The more rigorous are the environmental policy instruments that directly increase the financial burdens of companies due to environmentally harmful behaviour (such as taxes or emission standards), the more stringent is the environmental policy. However, in the case of environmental policy instruments in the form of subsidies rewarding pro-ecological behaviour (*e.g.* tax reliefs and exemptions related to environmental protection, environmental subsidies for research and development), a higher level of support means a more rigorous environmental policy, because it increases the opportunity cost of pollution, thus giving an advantage to 'cleaner' business operations (Botta & Koźluk, 2014).

The stringency of environmental policy can be evaluated based on the subjective opinions of various respondents (survey indicators), changes in energy prices, pollution abatement efforts and composite indices (Galeotti *et al.*, 2020) such as the Environmental Policy Stringency index (EPSI) developed by the OECD in 2014 and updated in 2022. The EPSI is based on aggregated data on selected environmental policy instruments, mainly related to the climate and air pollution rated on a scale from 0 to 6. The instruments included in the previous version of the EPSI were divided into market-based and non-market-based instruments. In the updated version of the EPSI, a new sub-index that measures the strength of technology support policies was added, complementing the previous index structure of market-based and non-market-based sub-indices. Technology support policies are further divided into upstream and downstream technology support instruments, *i.e.* R&D subsidies and feed-in-tariffs alongside with auctions for solar and wind energy technologies, respectively (Kruse *et al.*, 2022).

The impact of tightening environmental policy on the behaviour of enterprises is considered in the literature on environmental economics in the context of the pollution haven hypothesis and the Porter hypothesis. According to the former, differences among countries in terms of the restrictiveness of environmental policy may result in shifting highly polluting industries from industrialized economies to countries where environmental regulations are very lax or non-existent (Jobert *et al.*, 2019). The Porter hypothesis claims that the tightening of environmental requirements may increase the competitiveness of enterprises by encouraging them to seek and implement widely understood environmental innovations. Eco-innovation can lower costs, enhance productivity, and create new market opportunities. Firms that are pioneers in implementing innovative proecological solutions on the market may benefit in particular (Porter & van der Linde, 1995).

The role of environmental policy stringency in inducing eco-innovation claimed by the Porter hypothesis has been a subject of interest in many research studies. The analyses carried out concern both the entire environmental policy as well as individual instruments of this policy.

One of the early studies on the determinants of eco-innovation is a study conducted by Brunnermeier and Cohen (2003) on panel data for US manufacturing industries in 1983-1992. Their research confirms the positive impact of the change in pollution abatement expenditures on the number of successful environmental patent applications granted to the industry. It also shows that increased monitoring and enforcement of existing regulations has not provided additional incentives for innovation. A similar proxy of environmental policy stringency (*i.e.* pollution abatement and control expenditures) was used by Rubashkina *et al.* (2015) in their study on the impact of environmental regulation on manufacturing sectors in 17 European countries between 1997 and 2009. Their findings indicate a positive influence of strict environmental policy on innovation activity, measured by patents.

Using the sample of 25 countries (including European countries, the United States and Japan) over the period of 1990-2015, D'Amato *et al.* (2021) show that a stronger environmental policy commitment provides a signal encouraging eco-innovative efforts. Moreover, research results by Fusillo *et al.* (2019) indicate that there is a strong and positive relationship between the stringency of the environmental policy and the generation of green technological knowledge at the firm level based on the sample of European firms in 2005-2012. Based on the QARDL model over the period 1995-2020 in China, Alzakri (2023) found that in the long run, higher environmental policy stringency fosters environmental innovation and in the short run at higher quantiles only. Research by Johnstone *et al.* (2012) and Hassan and Rousselière (2022) also confirm that strict environmental policies lead to increased eco-innovation activities. However, contrary conclusions come from a cross-country study by Van Kemenade and Teixeira (2017). Environmental policy stringency measured by them using mainly perception-based data did not turn out to be a significant determinant for eco-innovation performance.

Hassan and Rousselière (2022) and Zhang *et al.* (2022) suggest that non-market instruments are more effective than market ones in stimulating eco-innovation. However, De Santis and Jona Lasinio (2016) and Fabrizi *et al.* (2018) present opposite conclusions.

Johnstone *et al.* (2010) show that the effectiveness of using alternative instruments for inducing innovation in renewable energy sources depends on the technology type. Broad-based policies (*e.g.* tradeable energy certificates) are more likely to foster technological innovations in sources that have achieved or are approaching competitiveness with fossil fuel sources, such as wind power. To encourage innovation in more costly renewable energy technologies such as solar energy, more targeted subsidies such as feed-in tariffs may be required.

Palage *et al.* (2019) examined the innovation impacts of renewable energy policy on solar photovoltaic technology. Their findings reveal that public R&D support, feed-in-tariffs and renewable energy certificate schemes stimulate solar energy patenting activity, with the former being the most important.

The positive impact of standards on stimulating green innovation was confirmed by Lee *et al.* (2011), Klemetsen *et al.* (2018), Kesidou and Wu (2020), and Zhang and Zhao (2023) and rejected by Wang *et al.* (2023).

The study by Kemp and Pontoglio (2011) shows that the significance of taxes and emissions trading in driving eco-innovation is much weaker than expected in the theory. Furthermore, environmental regulations such as standards are more likely to stimulate radical eco-innovations (*i.e.* those that imply technological discontinuity consisting in a break with existing competences and technologies) than market-based instruments.

The assessment of the impact of subsidies on eco-innovations in the empirical research literature is not unequivocal. Biscione *et al.* (2021) and Jové-Llopis and Segarra-Blasco (2018) indicate their insignificance in inducing eco-innovation while Stucki *et al.* (2018) show a positive association between subsidies and green product innovation. Moreover, Stucki *et al.* (2018) suggest that if taxes do not trigger additional demand for green products or services, they reduce companies' willingness to innovate.

Da Silva *et al.* (2021) examined the impact of the stringency of the European Union Emissions Trading Scheme (EU ETS) on the eco-innovation activities of companies in 2012-2014 in 13 EU countries. They used the Community Innovation Survey data and a self-constructed indicator to capture the stringency of EU-ETS policy as a ratio between the emissions and allowances allocated to individual industry sectors. Their findings show that the EU-ETS has barely affected companies' eco-innovation activities.

According to the results of the research by Horbach *et al.* (2012) based on the German Community Innovation Survey data, regulations notably foster eco-innovations concerning air, hazardous substances, and recyclability of products, whereas environmental taxes are crucial for fostering innovations lowering material and energy use.

In summary, most studies show that stricter environmental policies stimulate eco-innovation. However, which instruments of this policy are the most effective remains an open question.

Based on the above previous empirical results, I adopted the following research hypotheses:

H1: The overall stringency of environmental policy has a positive impact on the eco-innovation level.

H2: The stringency of technology support instruments stimulates eco-innovation more effectively than the stringency of market-based and non-market-based instruments.

H3: The stringency of R&D subsidies stimulates eco-innovation more effectively than the stringency of feed-in tariffs and auctions for renewable energy.

RESEARCH METHODOLOGY

In this study, I used a quantitative methodology, *i.e.* panel regression analysis. I examined the impact of environmental policy stringency on eco-innovation at three levels considering:

- the overall level of this strictness;
- the stringency of three groups of instruments (market-based, non-market-based and technology support instruments);
- the stringency of three individual instruments belonging to the group of technology support policies.

The level of eco-innovation can be measured in two aspects: innovation input and innovation output (Wen *et al.*, 2023). This study followed the latter approach and used 'green' patent data (PAT) as the measure of the eco-innovation following D'Amato *et al.* (2021), Hu *et al.* (2023) and Sun *et al.* (2019).

The relationship between environmental policy stringency and the eco-innovation, corresponding to the above-mentioned three levels is assumed to be represented in the following models:

$$PAT_{i,t} = EPS_{i,t}\beta_1 + CON_{i,t-1}\beta' + v_{i,t} \quad (1)$$

$$PAT_{i,t} = MARK_{i,t}\beta_1 + NON\_MARK_{i,t}\beta_2 + TECH\_SUP_{i,t}\beta_3 + CON_{i,t-1}\beta' + v_{i,t} \quad (2)$$

$$PAT_{i,t} = SUB_{i,t}\beta_1 + SOL_{i,t}\beta_2 + WIN_{i,t}\beta_3 + CON_{i,t-1}\beta' + v_{i,t} \quad (3)$$

in which:

$PAT_{i,t}$ - eco-innovation related patents;
$EPS_{i,t}$ - overall environmental policy stringency;
$MARK_{i,t}$ - stringency of market-based instruments;
$NON\_MARK_{i,t}$ - stringency of non-market-based instruments;
$TECH\_SUP_{i,t}$ - stringency of technology support instruments;
$SUB_{i,t}$ - stringency of subsidies for R&D on low-carbon energy technologies;
$SOL_{i,t}$ - stringency of feed-in tariffs and auctions for solar energy technologies;
$WIN_{i,t}$ - stringency of feed-in tariffs and auctions for wind energy technologies;
$CON_{i,t-1}$ - a vector of lagged control variables;
$v_{i,t}$ - a total random error consisting of a purely random part $\varepsilon_{i,t}$ and an individual effect u_i referring to the specific unit i of the panel ($v_{i,t} = \varepsilon_{i,t} + u_i$);
$\beta_1, \beta_2, \beta_3$ - parameters;
β' - a vector of parameters;
i - the index i =1,2, ...,N denoting objects (countries);
t - the index t =1,2, ...,T denoting time units.

Control variables used in models (1)-(3) include gross domestic product per capita (GDP), material import dependency (MAT_IMP), and human resources in science and technology (HUM_RES). Table 1 presents full definitions of the variables used in the models.

A higher level of GDP can enhance green innovation by providing the financial resources necessary to invest in research and development of environmentally friendly technologies and by shifting public priorities towards better environmental quality and green technologies (Alzakri, 2023). Empirical studies by D'Amato *et al.* (2021) and Johnstone *et al.* (2012) have shown a positive effect of GDP on eco-innovation. Human resources for science and technology (*e.g.* researchers, people employed in science and technology occupations) are a crucial factor in the process of innovative development and foster innovation and patent activity (Pater & Lewandowska, 2015; Teslenko *et al.*, 2021). High level of material import dependency, *i.e.* the significant extent to which an economy relies on imports to meet its material needs in terms of fossil fuel energy materials, metal ores, non-metallic materials, and biomass (Zecca *et al.*, 2023) can be a factor stimulating eco-innovation undertaken to replace these materials or reduce the demand for them.

Table 1. Description of variables used in models

Variables	Definitions	Data sources
Dependent variable		
PAT	Eco-innovation-related patents per million population (natural logarithm)	Eco-innovation Scoreboard (European Commission)[1]
Independent variables		
EPS	Environmental policy stringency index	OECD[2]
MARK	Stringency index of market-based environmental policy instruments	OECD[2]
NON_MARK	Stringency index of non-market-based environmental policy instruments	OECD[2]
TECH_SUP	Stringency index of technology support policy instruments	OECD[2]
SUB	Stringency of subsidies for R&D on low-carbon energy technologies	OECD[2]
SOL	Stringency of feed-in tariffs and auctions for solar energy technologies	OECD[2]
WIN	Stringency of feed-in tariffs and auctions for wind energy technologies	OECD[2]
Control variables		
GDP	Gross domestic product per capita, PPP (constant 2017 international $)	World Bank[3]
MAT_IMP	Material import dependency expressed as the ratio of imports over direct material inputs in percentage	Eurostat[4]
HUM_RES	Human resources in science and technology as a share of the active population in the age group 25-64	Eurostat[4]

[1] https://green-business.ec.europa.eu/eco-innovation_en; [2] https://stats.oecd.org; [3] https://data.worldbank.org
[4] https://ec.europa.eu/eurostat
Source: own study.

The independent variables (EPS, MARK, NON_MARK, TECH_SUP, SUB, SOL and WIN) are not lagged, as it is assumed that the requirements and possible changes to the environmental policy are known to enterprises in advance.

In the analysis, I used the panel data on 18 EU countries (Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, the Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, and Sweden) encompassing eight years (2013-2020) (144 observations in total). The sample did not include all EU countries due to the lack of available data on the environmental policy stringency index developed by the OECD. Moreover, the adopted research period was determined by the data availability (*i.e.* data on the environmental policy stringency index and on eco-innovation-related patents). Table 1 presents the sources of the data used.

Due to the character of the data (panel data), I considered three types of estimators: ordinary least squares (OLS), fixed effects, and random effects models. I selected the most appropriate estimator based on the Breusch-Pagan test, and then, if necessary, on the basis of the Hausman test. The Breusch-Pagan test makes it possible to verify the occurrence of individual effects. The null hypothesis is that the variance of the individual effects component equals zero. Failure to reject this hypothesis means an insignificant change in variance when considering individual effects, therefore, adding these effects is redundant, and consequently the OLS estimator is adequate. In the case of individual effects, fixed and random effects should be considered. I made the choice between fixed effects and random effects based on the Hausman test, which compares the values of parameter estimates obtained by means of both estimators. Failure to reject the null hypothesis indicates the consistency of both estimators, with the random effects estimator being more efficient (Kufel, 2011, pp. 175, 179-180).

To verify the hypotheses, I adopted a significance level of 0.05. I used Gretl software to perform the necessary calculations.

RESULTS AND DISCUSSION

Table 2 provides the descriptive statistics for the dependent, independent and control variables. The eco-innovation-related patents per million population variable (PAT) was logarithmised and the average value of the natural logarithm of this variable was 4.26 with a maximum value of 5.06 (in Germany in 2020 and in Sweden in 2018) and a minimum value of 2.88 in Portugal in 2018. Considering average values, the highest level of overall stringency of environmental policy (EPS) in 2013-2020 was recorded in France (4.30) and the lowest in Spain (2.37). The average value of the stringency of market-based instruments (MARK) during the period considered was 1.73. The maximum value of 4.17 occurred in France in 2019-2020 and the minimum value of 0.50 in Greece in 2013. The level of the stringency of non-market-based instruments (NON_MARK) in the analysed period was high in most countries (an average value of 5.50), with a minimum value of 4.25 in Greece in 2013 and a maximum value of 6.00 in Italy in 2016-2020. The stringency of technology support policy instruments (TECH_SUP) reached the average value of 2.27. The maximum value of 5.25 was recorded in France in 2013 and the minimum value of 0.50 in Ireland, Poland, Portugal, Slovakia, and Spain (in different years). Finally, on average the level of stringency of subsidies (SUB) with a value of 2.46 was higher than that of price support instruments for wind energy technologies (WIN) with a value of 2.29 and that of price support instruments for solar energy technologies (SOL) with a value of 1.88.

Table 2. Descriptive statistics of variables used in the regression models

Variables	Mean	Standard deviation	Minimum	Maximum
PAT	4.26	0.574	2.88	5.06
EPS	3.17	0.560	2.11	4.89
MARK	1.73	0.946	0.50	4.17
NON_MARK	5.50	0.174	4.25	6.00
TECH_SUP	2.27	1.23	0.50	5.25
SUB	2.46	1.50	1.00	6.00
SOL	1.88	2.06	0.00	6.00
WIN	2.29	2.13	0.00	6.00
GDP	42 832	11 953	24 816	86 926
MAT_IMP	39.10	15.20	16.00	80.60
HUM_RES	46.5	8.24	28.70	60.70

Source: own study.

The values of variance inflation factors (*i.e.* lower than 10) indicated that the problem of multicollinearity did not occur in any of the three models used (cf. Table 3).

Table 4 presents the estimation results of panel regression for the model (1) using the ordinary least squares method. I chose between the panel model estimated by the OLS method and the model with fixed or random effects based on the Breusch-Pagan test. The null hypothesis assumed that the variance of the individual effects component was equal to zero. Rejecting the null hypothesis (chi-square statistic = 2.59514, p-value = 0.107192) means that the change in variance with the introduction of individual effects is negligible, thus, adding these effects is redundant. Therefore, the results of the Breusch-Pagan test justify the use of the OLS method to estimate the model (1), representing the effect of the overall level of environmental policy stringency on the eco-innovation-related patents. According to the estimation results, this stringency, alongside with the GDP per capita and the human resources in science and technology proved to be significant variables. The estimated model satisfies the assumptions about the normality of the residuals. It was checked by the Doornik-Hansen test (chi-square statistic = 0.722, p-value = 0.69689). However, there is a problem with heteroscedasticity (according to the Wald test results: chi-square statistic = 44.3099, p-value < 0.001). The occurrence of heteroscedasticity makes it difficult to verify the model due to unreliable results of significance tests, therefore, model (1) cannot be accepted in the analysis of the relationship of environmental policy stringency and the eco-innovation.

Table 3. Variance inflation factors for the regression models

Variables	Model (1)	Model (2)	Model (3)
EPS	1.215	–	–
MARK	–	1.596	–
NON_MARK	–	1.205	–
TECH_SUP	–	1.097	–
SUB	–	–	1.704
SOL	–	–	1.591
WIN	–	–	1.557
GDP	2.528	2.614	2.668
MAT_IMP	1.107	1.344	1.164
HUM_RES	2.625	3.014	3.562

Source: own study.

Table 4. Results of the OLS panel regression analysis for model (1)

Variables	Coefficient	Standard deviation	t-statistics
Constant	1.25081***	0.194481	6.432
EPS	0.375527***	0.0527423	7.120
GDP	1.26545e-05***	3.56431e-06	3.550
MAT_IMP	-0.000568659	0.00185996	-0.3057
HUM_RES	0.0278826***	0.00526845	5.292
No. of observations	144	**R-squared**	0.696648
Adjusted R-squared	0.687918	**p-value for test F**	4,89e-35

Note: *** means significance level at 1%.
Source: own study.

The model (2) represents the impact of market, non-market-based and technology support instruments of environmental policy on eco-innovation as measured by the patents. Table 5 shows the model estimation results based on the OLS method. The value of the Breusch-Pagan test (chi-square statistic = 0.738569, p-value = 0.39012) confirmed that the use of OLS panel regression instead of panel regression with fixed or random effects was justified. The estimated model met the assumptions of the OLS regression in terms of homoscedasticity (the results of the Wald test: chi-square statistic = 21.5178, p-value = 0.254099) and normality of the residuals (the results of the Doornik-Hansen test: chi-square statistic = 0.440401, p-value = 0.802358).

The stringency of non-market-based instruments does not significantly influence the eco-innovation, nor does the material import dependency. Statistically significant determinants of the eco-innovation are the stringency of market-based and technology support instruments, as well as the GDP per capita and the human resources in science and technology. Technology support instruments are both more significant and exert a greater impact on eco-innovation than market-based instruments.

Table 6 shows the estimation results of the model (3) that represents the relationship between the stringency of three instruments of technology support policy and the eco-innovation as measured by the patents. The result of the Breusch-Pagan test (chi-square statistic = 1.69538, p-value =0.192893) justifies the recognition of the OLS as the most appropriate model estimation method. The Doornik-Hansen test confirms the normality of the residuals (chi-square statistic = 0.33277, p-value = 0.84672) and the Wald test corroborates the homoscedasticity of the model (chi-square =

13.9434, p-value = 0.732774). The stringency of feed-in tariffs and auctions for solar energy technologies, as well as the material import dependency, turned out to be insignificant variables. On the other hand, the stringency of subsidies for R&D on low-carbon energy technologies, the stringency of feed-in tariffs and auctions for wind energy technologies as well as the GDP per capita and the human resources in science and technology, have a positive and significant impact on eco-innovation. Subsidies for R&D on low-carbon energy technologies are more effective in boosting eco-innovation than feed-in tariffs and auctions for wind energy technologies.

Table 5. Results of the OLS panel regression analysis for model (2)

Variables	Coefficient	Standard deviation	t-statistics
Constant	2.95354***	0.907905	3.253
MARK	0.0851297**	0.0347451	2.450
NON_MARK	-0.191574	0.164457	-1.165
TECH_SUP	0.166744***	0.0221222	7.537
GDP	1.28814e-05***	3.51934e-06	3.660
MAT_IMP	-0.00102468	0.00198994	-0.5149
HUM_RES	0.0283598***	0.00548162	5.174
No. of observations	144	**R-squared**	0.718109
Adjusted R-squared	0.705764	**p-value for test F**	2.74e-35

Note: ***, ** mean significance level at 1% and 5% respectively.
Source: own study.

Table 6. Results of the OLS panel regression analysis for model (3)

Variables	Coefficient	Standard deviation	t-statistics
Constant	2.09441***	0.185781	11.27
SUB	0.0997441***	0.0225682	4.420
SOL	0.00512013	0.0159183	0.3217
WIN	0.0620845***	0.0152270	4.077
GDP	1.22435e-05***	3.55508e-06	3.444
MAT_IMP	-0.00237903	0.00185161	-1.285
HUM_RES	0.0286721***	0.00595754	4.813
No. of observations	144	**R-squared**	0.718236
Adjusted R-squared	0.705896	**p-value for test F**	2.65e-35

Note: *** means significance level at 1%.
Source: own study.

In summary, the estimation results of model (2) indicate a significant impact of the stringency of technological support instruments and (to a lesser extent) market-based instruments on eco-innovation. They show no impact of the stringency of non-market-based instruments. Therefore, the hypothesis H2 was supported. According to the estimation results of model (3), the stringency of two of the three technological support instruments (*i.e.* R&D subsidies on low-carbon energy technologies and feed-in tariffs and auctions for wind energy technologies) turned out to be important factors stimulating eco-innovation, with the former being more effective. These findings confirm the hypothesis H3.

Due to the difficulty of verifying model (1), it was not possible to support or deny the significant role of the overall environmental policy stringency in triggering eco-innovation, the existence of which is confirmed, among others, by Rubashkina *et al.* (2015), D'Amato *et al.* (2021) and Hassan and Rousselière (2022). Therefore, hypothesis H1 could not be confirmed or rejected.

According to the research results, strict non-market-based instruments turned out not to incentivize firms for eco-innovation activity. This conclusion is in accordance with the findings of the study by De Santis and Jona Lasinio (2016) and in contrast with the results obtained by Klemetsen *et al.* (2018). The sub-index of non-market-based instruments (according to the OECD methodology) covers emission standards, including emission limits for nitrogen oxides (NOx), sulfur oxides (SOx), particulate matter and sulfur content limit for diesel (Kruse *et al.,* 2022, p. 11). The stringency level of these standards in EU countries has been very high for years (as measured by the index developed by the OECD). It is thus possible that the development level of technologies used in EU countries aimed at abatement of these pollutants is so advanced that the technical possibilities of enhancing innovation in this area are limited (with the current state of knowledge). Moreover, as argued by Barbera and McConell (1990) (cited in Wang *et al.*, 2023), the insignificance of standards in stimulating eco-innovation may result from the fact that, after adopting specific target technologies, companies usually lack motivation to continue investing in the development of other environmentally friendly technologies.

The research results reveal that higher stringency of market-based instruments has a positive impact on eco-innovation-related patents in EU countries. The market-based instruments taken into account according to the OECD methodology of the EPSI (Kruse *et al.*, 2022, p. 11), include carbon dioxide (CO_2) and renewable energy trading schemes, and taxes on CO_2, NOx, SOx, and fuel. Similar research results confirming the significance of market-based instruments in terms of stimulating eco-innovation were obtained among others by De Santis and Jona Lasinio (2016) and Fabrizi *et al.* (2018). Market-based instruments give companies greater flexibility in choosing technologies to reduce compliance costs and can thus provide greater incentives for innovation than non-market-based ones.

The research results indicate that stringent technology support instruments as compared to market-based and non-market-based ones are the most suitable to stimulate eco-innovation. These instruments aim to promote the development and the adoption of specific environmentally friendly technologies. However, individual technology support instruments differ in their impact on stimulating eco-innovation. The most effective are subsidies for R&D on low-carbon energy technologies. This finding is in line with the results of the study by Palage *et al.* (2019) who claim that public R&D support is more influential than feed-in tariffs and renewable energy certificate schemes in fostering solar energy innovation. The effectiveness of stringent feed-in tariffs alongside with auctions in encouraging companies to engage in eco-innovation has only been proven for instruments targeting wind energy technologies and not for solar energy technologies. This can presumably be explained by differences in innovation potential and learning by doing opportunities between the two renewable energy technologies. According to Nemet (2012), knowledge gained from experience shows diminishing returns. Perhaps the innovation potential for solar energy technologies through learning by doing is lower than for wind energy ones and price support instruments are no longer effective in stimulating innovation for solar energy technologies. Another explanation may be a more effective exchange of experience between the producer and the user of the technology in the case of wind energy than solar energy (wind farm developer versus a largely mass user).

CONCLUSIONS

This study examined the relationship between environmental policy stringency and the eco-innovation level measured by patents based on panel data on 18 EU countries in 2013-2020. According to the research results, the importance of the stringency of environmental policy in triggering eco-innovation varies depending on the instruments of this policy. Higher stringency of technology support and market-based instruments positively influences eco-innovation whereas more strict non-market-based instruments do not impact eco-innovation. Technology support instruments are more effective in stimulating eco-innovation than market-based instruments. Individual technology support instruments differ in their impact on eco-innovation, with R&D subsidies being the most important. The stringency of feed-in tariffs and auctions is a significant factor stimulating eco-innovation in the case of wind energy technologies, but not in the case of solar ones.

This study is not free from limitations. Firstly, it uses the number of patents as a measure of the level of eco-innovation, thereby ignoring other aspects of eco-innovation related to *e.g.* organisational change or marketing solution. Not all eco-innovations are patented by firms. Secondly, the index of environmental policy stringency developed by the OECD used in the analysis includes only instruments related to climate and air pollution policies and does not consider instruments targeting other areas of environmental protection, such as water or waste management.

The findings of this study provide the following recommendations for policymakers. Stringent technology support and market-based instruments are effective in stimulating eco-innovation in EU countries considered in the research sample. The environmental policy aimed at fostering eco-innovation should concentrate on increasing R&D subsidies for clean technologies. Further tightening emission standards in order to enhance eco-innovation level is not recommended.

The relationship between environmental policy stringency and eco-innovation needs further scientific examination. Future research could particularly focus on comparing the influence of alternative instruments on eco-innovation across technologies based on more detailed data on patent activity. Furthermore, it would be interesting to investigate the impact on eco-innovation of environmental policy instruments other than those relating to climate and air protection.

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Acknowledgements and Financial Disclosure

The author would like to thank the anonymous reviewers for their useful comments on a previous version of the manuscript.

Conflict of Interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Ministry of Education and Science
Republic of Poland

The journal is co-financed in the years 2022-2024 by the Ministry of Education and Science of the Republic of Poland in the framework of the ministerial programme “Development of Scientific Journals” (RCN) on the basis of contract no. RCN/SP/0251/2021/1 concluded on 13 October 2022 and being in force until 13 October 2024.