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The Patterns of Energy Innovation Convergence across European Countries

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Abstract: Energy innovation is critical for addressing climate change and the ecological transitions of both developed and emerging economies. The present paper aims at the identification and assessment of patterns in energy innovation convergence across a sample of 27 European countries over the period 2000–2018. The research is based on data covering a broad category of patents related to climate change mitigation technologies in the energy sector, including combustion inventions with mitigation potential (e.g., using biomass), extracted from the Organisation for Economic Co-operation and Development (OECD) Statistical Database. Using a nonlinear time-varying factor model, the paper demonstrates that energy innovation efforts in the examined sample follow a pattern of club convergence. The findings allow the identification of three convergence clubs characterised by distinct disparities in energy patent intensity, as measured by the number of patent applications per 10 million inhabitants. Moreover, the results of an ordered logit model demonstrate that the emergence of the identified convergence clubs might be attributable to initial differences in per capita environmental research and development (R&D) expenditure, human resources in science and technology (HRST), and environmental policy stringency. The findings have important policy implications as they suggest the need for more tailored policies based on smart development and specialization frameworks designed to boost the energy innovation performance of the laggard countries, more fully exploiting the potential of their less technologically advanced sectors, such as agriculture.

Keywords: energy innovation; energy patents; convergence; club convergence; R&D expenditure; HRST; environmental policy stringency

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1. Introduction

Facing the constantly growing consumption of energy in the world on the one hand, and the scarcity of natural resources and the looming perspective of climate change on the other, the search for new sources of energy, increasing the use of renewable ones, and improving their efficiency inevitably become the central issues of sustainable development and ecological transition of both developed and emerging economies. Reduction of the harmful environmental impacts of energy production and consumption is of crucial relevance from the standpoint of policies aiming at mitigation of adverse consequences of climate change. Not surprisingly, therefore, the issues related to those processes constitute the most important dimensions of contemporary environmental protection frameworks [1].

The intensity and efficiency of innovative activities in the field of energy become critical for addressing key challenges related to environmental protection and ensuring a more sustainable consumption of natural resources, such as energy security, combating pollution or limiting global warming. Other vital challenges in the area of energy include improving access to modern energy carriers, in particular electricity, and the security and resiliency of energy supply and distribution systems [2]. The development of more efficient and less polluting technologies related to energy use, supply and conversion is, therefore, undoubtedly one of the most important and socially desirable directions of international technological progress. Given the complexity and turbulent nature of the contemporary socio-economic environment, successful energy innovations often result from collective learning processes combining knowledge, skills, R&D and the deployment efforts of suppliers and users of particular technologies. It is worth pointing out, however, that such processes are usually possible only in specific contexts and within particular incentive structures [3]. Mutual relationships and feedback between the economic, environmental, and political dimensions of energy efficiency and sustainability render the ecological transition of the energy sector a particularly difficult issue. Every energy strategy must accommodate a multitude of often conflicting goals related to security, reliability, ecological performance, and costs of possible energy sources [4].

Energy innovation processes are often impeded by intrinsic structural weaknesses which tend to hamper both demand for the new technologies and the short-term business prospects of their potential providers. Firstly, the large scale of necessary investment outlays as well as significant technological and regulatory inertia of existing energy systems render the lead times needed to provide new technologies to mass market use particularly long. Secondly, new energy technologies are usually more expensive and not necessarily more effective than the existing substitutes, which likely slows down the pace of market penetration. Moreover, in the particular context of eco-innovations in the field of energy, the direct benefits accrue primarily to society as a whole, rather than the final users. Finally, energy innovations typically have to confront a multitude of barriers to entry, including, in particular, incompatibility of existing network infrastructure, extensive market power of key competitors, price controls or unstable regulatory frameworks. In the light of the above difficulties, successful market implementation of energy innovations largely depends on public policy support [5] (p. 3).

The so-called Porter hypothesis claims that "the properly designed environmental standards can trigger innovation that may partially or more than fully offset the costs of complying with them" [6] (p. 98). What is worth pointing out, however, is that innovation is likely driven not only by the quantity of regulations but primarily by their stringency. Additionally, as Fabrizi et al. [7] demonstrate, the effectiveness of environmental regulation policies can be increased by combining them with appropriate innovation policies. The actual impact of environmental regulation on innovation performance has been explored by an increasing bulk of studies, e.g., [8,9]. Furthermore, as a type of an environmental innovation, energy innovation has a "double externality" nature. As Rennings [10] (pp. 325–326) stresses, environmental innovation reduces negative environmental externalities and it is subject to externalities arising from knowledge spill-overs involving both environmental and standard innovation processes. Both these externalities, however, result in sub-optimal investment in environmental innovation, thus indicating the importance of the regulatory framework.

The general directions for ecological transition of energy sectors worldwide result from the Paris Agreement on climate change adopted in 2015 by nearly 200 countries [11]. The challenges related to the mitigation of adverse consequences of climate change increase the importance of innovation in all the major areas of contemporary energy policies, i.e., energy conversion, distribution and use. Effectiveness of energy innovation impacts a broad spectrum of energy development policy goals, including energy security, access, cost, international competitiveness, modernization of energy systems and reduction of adverse environmental impact [12]. At the national level the development of energy innovation policy is not only constrained by existing institutional, economic and social factors, but also involves multiple stakeholders, often with conflicting interests. In turn, policy guidelines shape each country's energy innovation development and deployment models. In the context of the EU, a policy framework for energy research and innovation activities is outlined in several strategic documents: the Strategic Energy Technology Plan (originally issued in 2007 [5] and revised in 2015 [13]), and the 'Accelerating Clean Energy Innovation' communication from the European Commission, adopted as an integral part of the 'Clean energy for all Europeans' package [14], following the Paris Agreement [11]. Given the fact that contemporarily energy is responsible for more than 75% of the EU's greenhouse gas (GHG) emissions [15], energy innovations become critically important for successful transition towards climate neutrality. To tackle the key environmental and climate-related challenges by decoupling economic growth from resource use and achieving climate neutrality (no net emissions of GHG) by 2050, a new EU strategy, the *European Green Deal*, was designed [16]. The strategy strongly emphasizes the role of cross-border and regional cooperation in achieving the benefits of clean energy at affordable prices, as well as the need for efficient regulatory framework and financing schemes to foster the deployment of innovative energy technologies and infrastructure. The research and innovation efforts in the field of energy are to be supported by the full range of instruments available under the *Horizon Europe* programme [17]. Given the specificity and the aforementioned structural weaknesses of energy innovation processes, the programme aims at fostering initiatives designed to combine societal pull and technology push effects.

Although energy innovation leading to transformational changes in energy sector is vital for limiting the adverse consequences of global climate change, no single country seems capable of addressing all the related energy and environmental challenges alone [18]. As demonstrated by Costantini et al. [19], the speed of innovation in the renewable energy sector is higher if more countries are engaged in R&D and invention activities. Innovative capacity, however, is not uniformly distributed across countries, which in turn results in significant disparities both in the actual effectiveness of R&D efforts, as well as in general approach to the creation of new knowledge. This problem is particularly important in the context of the European Union, which has set convergence across the Member States as one of its key priorities, and recognized innovation policy as a fundamental instrument in reaching this goal [20]. Moreover, as argued by Archibugi and Coco [21], reduction of cross-country disparities in innovative capacity is also a vital condition for boosting the global competitiveness of the EU's economy.

As economic growth is driven primarily by technological progress and innovation [22], long-run economic convergence is largely dependent on technological convergence. According to Jungmittag [23], given varying production technologies across countries, the convergence of national innovation capabilities (i.e., adoption and accumulation of technologies) is a *sine qua non* condition of the convergence in terms of labour productivities and per capita incomes. The convergence of labour productivities is largely driven by the diffusion of technologies, which in turn becomes a crucial determinant of economic growth for the catching-up countries. At the same time, for the advanced economies, transferable technological knowledge is the level of Ricardian technological specialization. In turn, larger differences in the level of technological specialisation are likely to impede the process of convergence.

Although economic integration fosters dissemination of innovative infrastructure, it may also exert the exactly opposite effect on the very creation of new knowledge and innovations, which tend to agglomerate in the most developed regions [20]. The return on investment in technological research usually increases in the areas where other research activities take place [24], in particular due to "agglomeration effects" and other kinds of positive spillovers and externalities resultant from geographical proximity [25]. Inventive firms and researchers are, therefore, often attracted to locations of intense innovative activities in a given field, where the returns on new knowledge tend to be much larger than in a less competitive environment of laggard regions [26].

Following Sharp [27], convergence in terms of innovation performance becomes an important driver of successful integration, as innovations foster not only economic performance, but also general socio-political cohesion. The latter notion is particularly important from the standpoint of overcoming aforementioned structural weaknesses of energy innovation.

Given the above, patterns of energy innovation convergence might shape the progress in reaching the policy goals regarding mitigation of the adverse consequences of climate change in Europe. Investigation of these patterns in the long run not only becomes an interesting research problem, but also might have important policy implications.

An assessment of the outcomes of innovation activities in the field of energy oriented towards mitigation of the adverse consequences of climate change is, however, not an easy task. One of the approaches to the above issue most commonly adopted in the relevant literature is based on the analyses of patent intensity, see e.g., [26,28,29], as measured by the number of energy patent applications per a given number of inhabitants [30].

The convergence in terms of patenting activity implies that countries exhibiting lower initial levels of patent intensity over time increase their innovative capacity, achieving higher rates of growth in per capita patent applications than their counterparts in the examined sample. This in turn allows them to gradually reduce their distance from the leaders.

The fact that knowledge is considered to be largely a public good might however render the issue of convergence in patent activity less important, since many countries may simultaneously benefit from their creation in one of them. Notwithstanding the above notion, several arguments of political and economic nature supporting the view that such a process is desirable might be brought up [17].

From an economic perspective, convergence in terms of patenting activity might indicate the improvement of innovation absorption capacity across the examined sample of countries, i.e., their ability to successfully adopt, adapt and implement knowledge created elsewhere. This capacity is, in turn, crucial not only from the standpoint of individual economies, as it enables them to guide their innovation efforts with respect to the conditions of the local markets for factors of production and improve their innovative productivity, but it also determines the directions and scale of international technology flows, see e.g., [31,32]. Following Cohen and Levinthal [33], it is worth pointing out, however, that the potential gains from technological spillovers are largely determined by the given country's past experience in relevant R&D. The improvement of innovation absorption capacity is also of crucial importance for the less technologically advanced economies, as it allows them to strengthen and expand their innovative potential and improves their resilience to external shocks.

The political importance of convergence in energy patent intensity, and in particular in the area of climate change mitigation technologies, results from its potential negative relationship with the scale of free-riding on innovation between countries. As demonstrated by Bosetti et al. [34], international knowledge spillovers typically encourage free-riding on already developed technologies, which likely crowds out domestic R&D investments. Higher convergence in energy patent intensity in the area of climate change mitigation technologies may therefore contribute to the limitation of innovation free-riding across countries. It may also reflect both the increasing engagement in the ecological transition of their energy sectors and public acceptance for the necessary costs of this process. In contrast, lower convergence within a largely homogenous regulatory environment suggests that some countries tend to free-ride on environmental-friendly solutions developed elsewhere. This in turn increases the risk that the innovation leaders might become discouraged from bearing disproportionately high costs of ecological transformation, which would make the achievement of the established energy policy targets even more difficult [35].

A vast majority of studies addressing convergence in the area of innovative capacity investigate the general dimension of these processes, abstracting from their course in particular technology fields, see e.g., [36–39]. Even though the relevant literature on energy innovation seems quite extensive (among others: [40–44]), to date only a couple of studies have directly addressed the problem of convergence in this area.

Using the data for 13 EU member countries over the period of 1990–2012, Grafström [26] found the evidence of conditional β- and σ-divergence in renewable energy innovation capabilities (patent applications per capita).This means that both the gap in patent intensity between innovation leaders and laggard countries and its dispersion increased in the examined period. It also implies that some EU countries tend to free-ride on the development efforts of other Member States. More recently, Bai et al. [45] examined trends in the renewable energy technology innovation (RETI) levels, as measured by the number of patents granted, adjusted for technology depreciation and diffusion, across the provinces of China over the period of 1997–2015 and found the evidence of club convergence. Their results demonstrate that over the examined period thirty provinces converged to three clubs characterized with significant disparities both in the level and the annual growth rate of RETI.

Given the above considerations and largely limited prior empirical evidence, the present study aims at the identification and assessment of patterns in energy innovation convergence in the area of climate change mitigation technologies across European countries.

The paper contributes to the relevant literature in three ways.

First, bearing in mind the complexity and multidimensionality of energy innovation, the study investigates a broader and more comprehensive category of patent applications related to climate change mitigation technologies in the energy sector that have sought protection in at least two jurisdictions. Such an approach allows reflection upon the relevant outcomes of R&D in the field of clean and energy saving technologies, irrespective of the industry in which they are introduced, which makes it a useful, direct and comprehensive proxy of the inventive activities oriented towards energy, e.g., [1]. Moreover, the paper examines a larger set of countries and a longer time span than prior research in the European context.

Second, the significant disparities in the innovative capacity between European countries, and the specificity of their individual development paths, render absolute convergence in terms of energy patent intensity in the field of climate change mitigation technologies highly unlikely. Therefore, given the historical, political, and socio-economic factors shaping the directions of technological progress in Europe, it can be hypothesized that patent intensity in the above area is characterised by the presence of convergence clubs. Given the above, the study makes an original attempt to delineate the related convergence clubs using the regression *t* test proposed by Phillips and Sul [46].

Third, the paper identifies and assesses the key determinants of the hypothesized club convergence. Given the evidence in the prior studies, it is likely that the energy innovation convergence paths are driven primarily by initial levels of the following factors: R&D, human capital and environmental policy-related measures. Therefore, the paper attempts to explain the emergence of the convergence clubs using the logit model by McKelvey and Zavoina [47].

The obtained results allowed the identification of three convergence clubs characterised by distinct disparities in energy patent intensity. The paper also demonstrates that the emergence of the identified convergence clubs might be attributable to the initial differences in per capita environmental R&D expenditure, HRST, and environmental policy stringency.

The remainder of the paper is organised as follows. Section 2 presents the methodological framework of the study and the details of the data selection procedures. Sections 3 and 4 present and discuss the results of the empirical analyses. The paper ends with conclusions recapitulating its main findings along with policy recommendations and suggestions for future research.

2. Materials and Methods

The examined sample covers 27 European countries, including 24 EU Member States, GB, Norway, and Switzerland, over the period 2000–2018, as determined by the availability of data on energy patent applications in the OECD Patent Database. [48]. Although other patent databases (see e.g., the World Intellectual Property Organization Patent Database) offer more recent data, the patent statistics presented in the OECD Patent Database are constructed using algorithms, which allows for the precise identification of climate change mitigation technologies related to energy generation, transmission or distribution. These technologies pertain to renewable energy generation, energy generation from fuels of non-fossil origin, nuclear energy, combustion inventions with mitigation potential (e.g., using biomass), inventions for efficient electrical power generation, transmission or distribution, and inventions with potential or indirect contribution to GHG emission mitigation. Therefore, relying on a single data source allows for the avoidance of potential issues related to data comparability. The number of inventions related to energy generation, transmission or distribution was identified by:

- Inventor country—fractional counts by country of residence of the inventor(s).
- Family size—"2 and greater", which counts only the higher-value inventions that have sought patent protection in at least two jurisdictions.
- Priority date—the first filing date worldwide.

Regarding factors potentially affecting the process of convergence club formation, the Eurostat and OECD datasets were used. The former includes R&D related to environmental protection per capita and human resources in science and technology (i.e., persons with tertiary education as percentage of active population). The latter relates to the Environmental Policy Stringency Index (EPS). It measures the degree to which environmental policies set a real or shadow price on environmentally undesirable activities primarily related to climate and air pollution. The index is scaled from zero to six, where six indicates the highest degree of stringency. The data on initial conditions refers to 2000.

To find convergence patterns in energy patent intensity across European countries, a regression t test proposed by Phillips and Sul [46] was applied. The test is based on the time varying factor representation of the convergence variable:

$$X_{it} = \delta_{it}\mu_t, \quad (1)$$

where μ_t is the common factor and δ_{it} is the time varying idiosyncratic distance from the common factor. In this study, X_{it} refers to energy patent intensity, as measured by the number of patent applications per 10 million inhabitants. The time varying element δ_{it} is modelled in semi-parametric form as:

$$\delta_{it} = \delta_i + \sigma_i \xi_{it} L(t)^{-1} t^{-\alpha}, \quad (2)$$

where δ_i is the time-invariant part of δ_{it}, σ_i is the idiosyncratic scale parameter, ξ_{it} is iid(0, 1) across i and weakly dependent over t, and $L(t)$ is a slowly varying function for which $L(t) \to \infty$ as $t \to \infty$.

Relative loading coefficient:

$$h_{it} = \frac{X_{it}}{N^{-1}\sum_{i=1}^{N} X_{it}} = \frac{\delta_{it}}{N^{-1}\sum_{i=1}^{N} \delta_{it}}, \quad (3)$$

measures the relation of the loading coefficient δ_{it} to the panel average at time t. As the cross sectional mean of h_{it} is unity, its variance is given by:

$$H_t = \frac{1}{N}\sum_{i=1}^{N} (h_{it} - 1)^2. \quad (4)$$

The convergence is present if $H_t \to \infty$ as $t \to \infty$.

Considering the approach of Philips and Sul [46], the null hypothesis of the convergence test is formulated as follows:

$$H_0: \ \delta_i = \delta \text{ and } \alpha \geq 0 \text{ against } H_1: \ \delta_i \neq \delta \text{ for all } i \text{ or } \alpha < 0. \tag{5}$$

The testing procedure consists of the following steps:

1. Calculation of cross-sectional variance ratios H_1/H_t (t = 1, 2, . . . , T).
2. Estimation of the following regression:

$$\log\left(\frac{H_1}{H_t}\right) - 2\log L(t) = a + b\log t + u_t, \text{ for } t = (rT),\ (rT) + 1,\ \ldots,\ T, \tag{6}$$

   where $r \in (0, 1)$. Following the results of their simulations, Philips and Sul [46] recommend the use of $r \in (0.2, 0.3)$. When T is small, r = 0.2 is preferred, and if T is large, r = 0.3 is better choice.
3. Application of autocorrelation and a heteroskedasticity robust one-sided t test to verify the null hypothesis $\alpha \geq 0$ using $\hat{b} = 2\hat{\alpha}$ and a HAC standard error. At a standard significance level (0.05), the null hypothesis is rejected if $t_{\hat{b}} < -1.65$.

Rejection of the null hypothesis means that there is no convergence in the group of all panel units. It does not imply, however, that there is no evidence of convergence in subgroups of units (i.e., club convergence). Philips and Sul [46] propose a specific procedure for testing club convergence. The algorithm includes four steps. First, the units are arranged in descending order with respect to the last period. Next, a core group is formed by adding countries one after another to a group of the two highest-patent countries at the start and performing the log t test up until the $t_{\hat{b}}$ for this group is larger than −1.65. Then, the log t test is performed again for this group and all the other units (one after another) forming the sample to determine if they converge. If they do not converge, the first three steps are performed for the all the other units. In the case that no clubs are identified, it means that those units diverge.

In order to explain the process of club formation within the sample of European countries, an ordered logit model pioneered by McKelvey and Zavoina [47] was used. This model designates every country to a particular club and allows for explaining variation in an ordered categorical dependent variable (i.e., belonging to alternative clubs ranked in line with the steady-state energy patent intensity of every club) as a function of independent variables.

3. Results

The log t test used for the whole sample indicates that the hypothesis of overall convergence can be rejected at the 5% significance level (−6.2339). As a consequence, the procedure for testing club convergence was applied. Table 1 shows summary results for the clustering and merging test procedures (i.e., the number of clubs and countries belonging to the particular club, the estimated parameters, and the standard errors).

Table 1. Summary results for the log t test.

Club	No. of Countries	$\hat{b}$	SE	t
1	8	0.2321	0.6459	0.3594
2	11	−0.2362	0.2122	−1.1127
3	6	−0.2888	0.2546	−1.1347

The results of the analysis allowed the identification of 3 clubs and two non-converging countries (Denmark and Romania). Club 1, with the lowest energy patent intensity, includes: Bulgaria, Czech Republic, Greece, Hungary, Latvia, Lithuania, Luxembourg, and Poland. Club 2 is composed of medium energy patent active countries such as: Belgium, Estonia, Ireland, Italy, Netherlands, Norway, Portugal, Slovak Republic, Slovenia, Spain, and United Kingdom. The last club, with the highest energy patent intensity, is comprised of Austria, Finland, France, Germany, Sweden, and Switzerland. Figure 1 provides a visualization of club membership. Interestingly, club 1 is dominated by Central and Eastern European countries, whereas club 2 is more dispersed geographically and covers most parts of Europe. The smallest club (club 3) is formed of Western and Northwestern European countries. Geographic effects seem to be evident for club 1 and club 3.

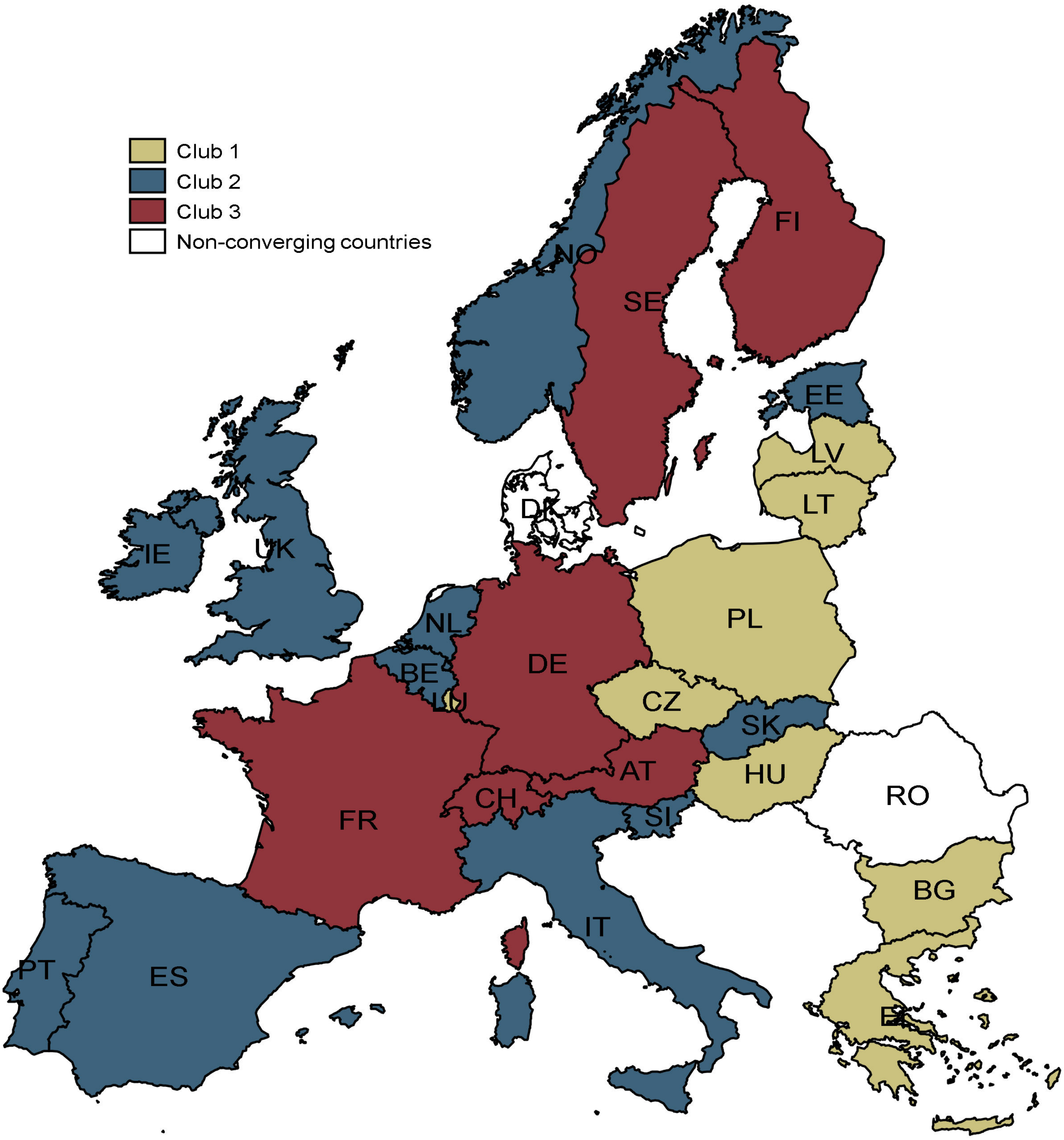


Figure 1. Spatial distribution of club members.

Figure 2 illustrates the change of energy patent intensities of the countries (in logs) belonging to particular clubs over the research period. As can be seen, there exists a catch-up effect, which is especially visible within club 2 and club 3, where countries with low energy patent intensities in 2000 are characterised by higher growth rates (i.e., the distances between points and the 45 degree line) than countries with medium and high energy patent intensities. Interestingly, the points representing countries of each club are distributed horizontally. Such a pattern of energy patent intensity distribution indicates indirectly the convergence processes to different steady states in each individual club. It is worth noting that in the case of club 1 the observed tendency is distorted by Luxembourg that significantly reduced patent intensity in the research period. This situation may result from the fact that Luxembourg's energy system is characterised by high import dependence.

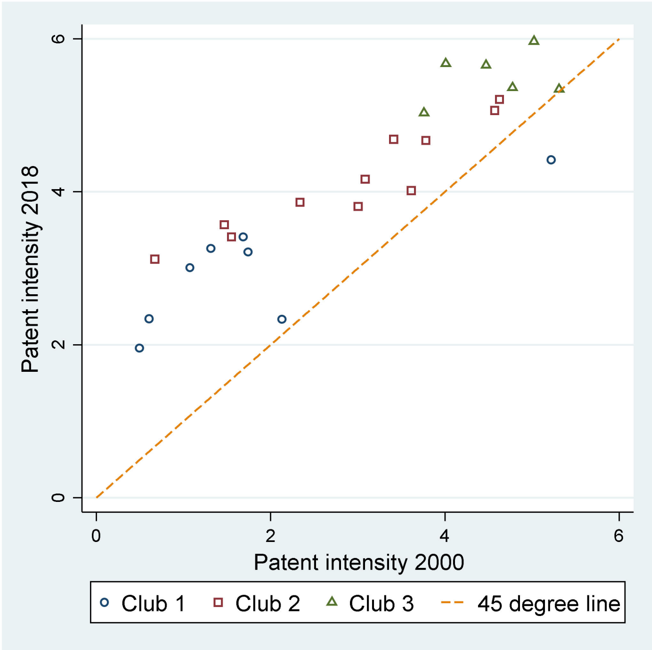


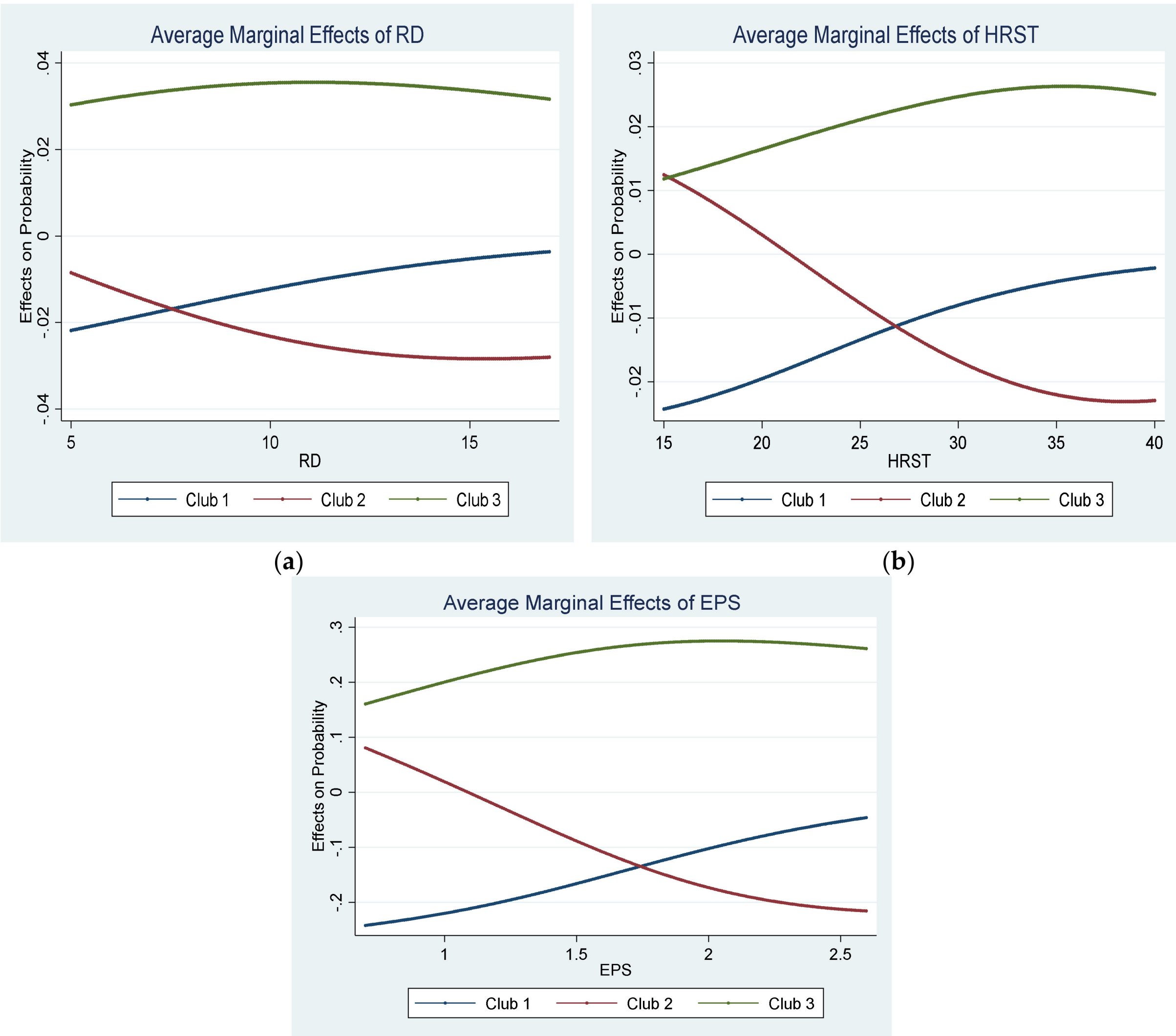
Figure 2. Shifts in energy patent intensity in clubs.

To find the factors influencing membership of a certain club, the ordered logit model was used with a three-level club membership—CM-outcome variable (coded 1, 2, 3) and three predictors: R&D related to environmental protection per capita—RD, human resources in science and technology—HRST, and the Environmental Policy Stringency Index—EPS. For the reasons of data availability, 5 countries were excluded from the analyses (i.e., Bulgaria, Estonia, Latvia, Lithuania, and Luxembourg). Due to non-intuitive interpretation of estimated coefficients of the ordered logit model, Table 2 presents the marginal effects, which show how the probabilities of each outcome (club membership) change with respect to changes in RD, HRST, and EPS. The marginal effects were computed as an average of the marginal effects at each value of covariates.

In the next step, the variations in marginal effects in response to the changes in the level of club membership determinants were examined (Figure 3). It should be noted that for higher levels of HRST, marginal effects increase for club 1 and club 3, but in the former case they remain negative. A similar trend is visible for the EPS variable and to some extent to the RD variable. In the case of club 2 the sign of marginal effects of the HRST variable and the EPS variable changes when we move from low values to high values of covariates, which results in the insignificance of marginal effect averages (see Table 2).

Table 2. Marginal effects on probabilities.

Variable		dy/dx	SE	*z*	*P* > *z*
RD					
	Club 1	−0.0213	0.010	−2.06	0.039
	Club 2	−0.008	0.005	−1.41	0.159
	Club 3	0.029	0.012	2.41	0.016
HRST					
	Club 1	−0.015	0.0047	−3.19	0.001
	Club 2	−0.005	0.005	−1.03	0.304
	Club 3	0.020	0.009	2.30	0.021
EPS					
	Club 1	−0.172	0.096	−1.80	0.071
	Club 2	−0.062	0.051	−1.21	0.228
	Club 3	0.234	0.123	1.91	0.056
Pseudo R2 = 0.2997, LR chi2(3) = 12.34					



(**a**) (**b**) (**c**)

Figure 3. Changes of marginal effects: (**a**) Marginal effects of RD; (**b**) Marginal effects of HRST; (**c**) Marginal effects of EPS.

The sign of the marginal effects of the RD variable indicates that a one-unit increase in R&D related to environmental protection increases the probability of belonging to the high energy patent intensity club. The opposite holds true for club 1. These findings are consistent with results of many general studies on the drivers of eco-innovation, where renewable energy patenting is regarded as a function of public R&D expenditures and the remaining factors [49–51]. On the other hand, R&D investment is a necessary but not sufficient condition to generate high quality inventions, since the effect of R&D expenditure is inherently uncertain and depends on the cumulative R&D capacity (learning-by-searching). For example, Nesta et al. [52] report the statistically insignificant effect of R&D on innovation activities in renewable energy and explain it by the omission of a patent quality dimension.

Concerning the marginal effects of HRST, the probability of club membership is explained well for club 1 and club 3. As with the marginal effects of RD, a one-unit increase in persons with tertiary education increases the probability of belonging to the high energy patent intensity club. The opposite effect can be observed for club 1. This means that specialised human capital is an important driver for countries patenting activities in energy. As suggested by Beise and Rennings [53] and Keller [54], a country's potential to become a leader in a particular field of technology results from its inventive and absorptive capacity formed by skilled human capital. In particular, tertiary education is often considered as one of the most valuable inputs into the inventive process in the field of eco-innovation. As reported by the OECD [55], several European countries (e.g., Germany and Sweden) have tailored their curricula or vocational training to environmental issues and eco-innovation.

Consistent with prior evidence in the relevant literature [1,45], the results of the present study indicate that the stringency of environmental policies plays an important role in shaping the trajectories of energy patent intensity across the European countries. In particular, higher stringency of environmental instruments increases the probability of being a member of the high energy patent intensive club. This finding supports the so-called Porter hypothesis. However, the interpretation of the results should take into account the fact that that the analysis was based on an aggregate measure of the stringency of environmental policy instruments. Therefore, the impact of its particular components on energy inventions trajectories remains unexplored and may vary according to the instrument type (i.e., market-based or non-market-based instrument) [7].

4. Discussion

The results of the research indicate the presence of club convergence in energy innovation across European countries over the years 2000–2018. The empirical evidence indicates that, over the analysed period, 25 out of the 27 examined countries have converged to three clubs characterised with significant disparities in energy patent intensity, as measured by the number of energy patent applications per 10 million inhabitants. These findings are generally in line with Bai et al. [45] who found evidence of club convergence in renewable energy technology innovation (RETI) across Chinese provinces and also identified three distinct clubs. Regarding the European context, delineation of the convergence clubs allowed the identification of a set of countries that are potentially most prone to free-riding on energy innovation efforts developed abroad. These results add value to the evidence provided by Grafström [26], who found conditional β- and σ-divergence in renewable energy invention capabilities across the 13 EU countries, suggesting that some of them tend to free-ride on the development efforts of other Member States.

Bearing in mind the complexity and multidimensionality of climate change mitigation challenges in the energy sector, unlike the prior studies on convergence in energy innovation that focused primarily on patents related to renewable energy technologies, the present research explores the patterns of energy innovation convergence using a broad category of patent applications in the field of climate change mitigation technologies.

Regarding patent applications as a proxy for innovation, it is important to keep in mind some drawbacks of using such a measure, arising, in particular, from the large disproportions in actual economic and technological performance of individual patents. In fact, many patented inventions have no or marginal economic value and quite short market life [56], as they turn out to be unattractive for the intended users, for instance due to technological underperformance or incompatibility with the existing infrastructure and complementary technologies. In contrast, a relatively small fraction of patents are often able to capture even over 90% of total monetary returns available in a given market (see e.g., [57] or [58]). Additionally, many patent applications are unsuccessful or do not ever become genuine innovations, which makes the linkages between patenting and the actual technological progress even harder to capture [59].

Moreover, given the complexity and difficulties inherent in patent application procedures, many smaller firms actually employ the effects of their research activities in production, attempting to veil them from competitors as trade secrets [60], without even trying to obtain a formal patent protection [61]. In addition, as pointed out by Schetino and Sterlacchini [62], the propensity to apply for patent protection is largely dependent on the individual firm's size, strategy, or ability to enforce patent rights, and thus varies significantly both across and within particular industries.

Due to the specificity of individual climate change-related technologies, both the effectiveness of patent protection rights and the propensity to patent differ significantly across diverse technological fields [59]. Moreover, different countries develop and apply different green technologies, basing on their suitability for a given geographical location, compatibility with a county's industrial structure and stage of development.

Notwithstanding the above limitations, a broad and comprehensive measure of patent applications employed in the present study allowed the capture of general patterns in energy innovation convergence in the European context.

The study has also identified three factors contributing to the emergence of the convergence clubs: i.e., per capita environmental R&D expenditures, HRST and environmental policy stringency. Given the above, the results indicate that the convergence paths in energy innovation intensity across the examined countries are determined by the initial levels of each of the above factors. These findings seem to be largely consistent with the results presented by Bai et al. [45], according to whom the convergence paths of individual Chinese provinces are shaped, in particular, by historical intensity of both R&D investment and environmental regulation. The results of the present study suggest that, due to the large gaps in the initial levels of the identified determinants between the weakest and the strongest countries, the former ones were largely unable to reduce the distance dividing them from technological leaders in the field of energy innovation.

Given the large distance still dividing many European economies from the established climate change mitigation goals [63,64] the success of the envisioned ecological transition depends critically on joint innovative effort and stronger inclusion of the laggard countries in the processes of technological convergence in the field of energy.

The emergence of the energy innovation convergence clubs might also be linked to the technological and industrial composition of particular economies. In the light of the so-called Porter hypothesis [6], the observed disparities in the relative energy innovation performance, as measured by patent intensity, might result from cross-country differences in the effective reach of environmental regulations. As demonstrated by [65], unregulated enterprises tend to exhibit a relatively low propensity to innovate in comparison to regulated ones. Additionally, in light of prior studies [64], willingness to engage in the development of climate change mitigation technologies appears to be driven by the actual costs of polluting. If such costs are relatively low, enterprises typically lack incentives to invest in environmental-friendly solutions.

Moreover, since the private sector appears to be generally more reluctant to innovate in the field of energy, trying to postpone costly ecological transition and reinforce the existing fossil-based paradigm, boosting the energy innovativeness of the laggard countries seems to be crucially dependent on public support for the related research, development, and deployment of innovative technologies [66].

The presence of convergence clubs in terms of energy innovation has several important implications of economic, environmental, and political nature.

Given the fact that energy is an essential input in almost every productive activity and that technological progress and innovations play a crucial role in economic growth, the patterns of technological convergence in the energy sector likely affect the course of overall economic convergence in Europe. The revealed disparities in energy innovation performance within each of the identified convergence clubs might, therefore, shape the paths of economic growth of the corresponding countries [22]. The process of ecological transition generates a substantial demand for innovative environmental-friendly technologies and complementary investments. It also leads to the emergence of new market arenas, products, and services, as well as creation of new job opportunities and broader structural shifts in the labour markets [17]. As the global market for eco-innovation is currently estimated at about one trillion euro per annum and expected to triple its size by 2030, the area of eco-innovation is naturally offering the EU economy a unique opportunity to improve competitiveness and job creation [67]. This opportunity seems particularly important in the wake of the COVID-19 pandemic, as intensification of research, development, and technology deployment activities related to energy innovation might also become an important driver of economic recovery.

The existence of convergence clubs suggests a persistently uneven contribution of their 'members' to the collective effort of combating climate change. Such disproportions might, in turn, increase the overall costs of achieving the energy-related goals of environmental policy adopted by the European countries [35].

From a political perspective, a persistently uneven burden of energy innovation efforts poses a more general threat to the fulfillment of the adopted policy goals. While combating climate change depends critically on collective international effort, the countries belonging to the least innovative club appear to be more prone to free-riding on innovations developed abroad [26]. Given the above, the innovation leaders may gradually become discouraged by an unsatisfactory engagement of other countries in the development of climate change mitigation technologies related to energy [35].

Given the above, club convergence in the field of energy innovation suggests the need for more tailored policies, based on smart development and specialization strategies, rather than 'one-size-fits-all' frameworks. Such policies should take into account both the specificity of individual economies, as well as the existence of apparent path dependence in their long-run energy innovation performance. Therefore, the results seem to be in line with Tödtling and Trippl [68] who argue that there is no 'ideal model' for innovation policy as innovation activities differ strongly between central, peripheral, and old industrial areas.

As the results of the present study attribute the emergence of the identified convergence clubs to the initial differences in environmental R&D expenditure, HRST and environmental policy stringency, it seems that the suggested revision of the relevant policies may be focused precisely on these areas. Additionally, the identified positive impact of the above variables on energy innovation performance seems to corroborate the findings of Fabrizi et al. [7] who demonstrate that the effectiveness of environmental regulation policies might be improved by an appropriate innovation policy.

In particular, boosting the relative innovation performance of the countries belonging to the least-innovative club might require the development and implementation of special economic incentives and financing schemes allowing them to more fully exploit the innovative potential of their less technologically advanced sectors, such as agriculture, and to increase R&D efforts and HRST engaged in the search for innovative solutions in the field of energy. Properly designed policies and incentives may therefore allow them to reduce the distance from the innovation leaders faster.

Theoretically, the same goal can be achieved by increasing the stringency of the relevant environmental policies or their reach. However, given the fact that weaker innovative performance is usually associated with a lower level of overall economic and technological development, such a solution would imply that the less advanced countries would have to comply with more stringent policies. This, in turn, could likely raise doubts about the fairness of such an approach and cause an increasing reluctance towards its adoption. Moreover, given the prior empirical evidence, suggesting the existence of optimal limits to the regulation stringency, the latter solution bears the risk of overregulation, which would likely impede the innovative performance of the laggard countries. Given the above, the identified club convergence and the related problem of free-riding on energy innovation should be addressed primarily by properly designed incentives oriented towards increasing the R&D expenditure and HRST in that field.

5. Conclusions

The present study aimed at the identification and assessment of patterns in energy innovation convergence across a sample of 27 European countries, including 24 current EU Member States, GB, Norway and Switzerland, over the period 2000–2018. The results of the conducted analyses indicate that energy innovation efforts in the area of climate change mitigation technologies, as measured by the number of patent applications per 10 million inhabitants, follow the pattern of club convergence.

The novelty of the paper arises from the following aspects. First, unlike previous energy innovation convergence studies that focused on renewable energy, it investigates a broad and comprehensive category of patent applications in the area of climate change mitigation technologies related to energy production, transmission or distribution. Moreover, the examined sample covers a larger set of countries and a longer time span than prior research in the European context. Second, to the Authors' knowledge, the present study is the first to find and delineate energy innovation convergence clubs in Europe. Third, the conducted analyses allowed the identification and assessment of the key factors that had contributed to the emergence of the identified clubs.

Consistent with prior research, the findings suggest a lack of overall convergence in energy innovation performance in the European context. The present study, however, enhances the existing literature on convergence patterns in the field of energy-related innovation by the identification of three distinct convergence clubs. The strongest energy innovation performance is observed in the club composed of the advanced economies of Western and North-Western Europe, while the 'laggard' one is dominated by Central and Eastern European countries. The observed disparities in energy patent intensity suggest a risk of free-riding on energy innovation.

As the mitigation of adverse consequences of climate change requires collective engagement of the European countries, the observed disparities may be addressed by proper policy actions. Since the obtained results attribute the emergence of energy innovation convergence clubs to the initial gaps in per capita environmental R&D expenditure, HRST, and environmental policy stringency between the countries exhibiting the lowest patent intensity and the innovation leaders the revision of policy should focus particularly on these areas. Therefore, the above findings suggest the need for more tailored policies based on smart development and specialization strategies designed to boost the energy innovation performance of the laggard countries, more fully exploiting the potential of their less technologically advanced sectors, such as agriculture. Given the risk of overregulation resultant from implementation of more stringent policies, fostering R&D and HRST by economic incentives and financing schemes oriented towards laggard countries seems to be the preferred direction of policy revision.

The main limitation of the study results from the incompleteness of the long-run statistical data that has rendered the exploration of the patterns of energy innovation convergence in the field of climate change mitigation technologies and their determinants across a larger set of European countries not possible.

Given the importance of the formulated research problem and its policy implications, the conducted analyses could be further extended by assessing the impact of a broader set of determinants shaping the course of convergence in the area of energy innovation.

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