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Environmental innovations in the EU: A club convergence analysis of the eco-innovation index and driving factors of the clusters

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A B S T R A C T

Eco-innovation, which combines innovation and sustainable development, has become an essential instrument to strengthen economic growth and preserve the environment. Considering the eco-innovation index for the EU, we study the convergence of eco-innovation across countries for the period 2012–2021 through the club convergence approach. We evaluate if and to what extent EU countries are converging toward a homogenous eco-innovation dynamic pattern. Our results indicate three clubs of convergence in the overall eco-innovation index, while the number of clusters is higher -four or five- in the five dimensions of the indicator. The analysis of the determinants of clubs in the aggregated index highlights the relevance of GDP per capita and economic openness, while R&D investments, environmental taxation and firm size are non-significant in our study. The results are also discussed within the contexts of convergence of environmental policies and innovation in the EU.

1. Introduction

Eco-innovation, a relatively recent concept in the literature (Fussler and James, 1996; Hemmelskamp *et al.* 1999; Rennings, 2000; Hellström, 2007; Horbach, 2008), is a powerful message that combines opportunities in reducing negative environmental externalities with fostering the socio-economic development pattern. Specifically, the communication "innovation[1] for a sustainable future –The Eco-innovation Action Plan (Eco-AP)" (European Commission, 2011, p.2) defines eco-innovation as "any form of innovation resulting in or aiming at significant and demonstrable progress towards the goal of sustainable development, through reducing impacts on the environment, enhancing resilience to environmental pressures, or achieving a more efficient and responsible use of natural resources". In sum, it focuses on achieving environmental objectives through innovation, and it is closely linked to an efficient use of natural resources and to low-impact production and consumption behaviours.

In a similar view, the Organization for Economic Co-operation and Development (OECD, 2009a, b) stresses two features differentiating eco-innovation from other types of innovation: 1) it is an innovation which results in a reduction of environmental impact; 2) the scope of eco-innovation may cross the boundaries of the body which produces the innovation and may involve changes in the existing sociocultural norms and institutional structures.

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[1] According to the Oslo Manual (OECD, 2018, p.20), an innovation is "a new or improved product or process (or combination thereof) that differs significantly from the unit's previous products or processes and that has been made available to potential users (product) or brought into use by the unit (process)".

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As a consequence of the relevance of this issue, eco-innovation has captured the attention of scholars. Interestingly, Hazarika and Zhang (2019) carry out a recent and systematic review of theories, classified in three categories (macro, *meso* and micro level) that have been used in order to interpret the different dimensions of eco-innovation. These categories depend on their scope and utility with respect to the dimensions of eco-innovation. The macro level comprises studies that highlight the role of institutions, regulations, policy interventions, and industrial techno-economic systems (Ball et al., 2018). The *meso* level theories deal with market dynamics, pressure groups, networking with other firms and institutions and customer needs (Rossignoli and Lionzo, 2018). Finally, the micro level includes theories that approach eco-innovation from the perspective of behavioural aspects such as organizational identity, availability of resources, financial issues, organizational identity, managerial concern, absorptive capacity (Arena et al., 2018).[2]

Certainly, eco-innovation and green technologies are at the heart of policy strategy developed in recent decades by the European Union (EU) and play a key role in the future development pathway, not just for the environmental implications, but also because they are now, and will be in the years to come, a principal source of employment, economic growth and new business opportunities (Castellacci et al., 2020). At the same time, workforce skills associated with the deployment and development of digital technologies are a key determinant of the capacity at national and local scales to specialize in green technologies (Santoalha et al., 2021), with a clear self-reinforcing mechanism of the technology evolution and the sustainable production and consumption pattern.

Indeed, eco-innovation is key to delivering many aspects of the circular economy (an economy that learns from nature in that it wastes nothing), such as industrial symbiosis or ecologies, cradle-to-cradle design and new, innovative business models, with cross-cutting solutions deriving from non-linear or, better still, circular systems of production and consumption (de Jesus *et al.*, 2018; Gente and Pattanaro, 2019).

Aware of the implications of the eco-innovation framework, the European Commission has continuously invested specific funding programs directed to enhance eco-innovation, for instance through the Competitiveness and Innovation Framework Programme (CIP), or the broad line of activity "Enabling the transition towards a green economy and society through eco-innovation" of the Horizon 2020, within the Next Generation EU, or more specifically within the New European Green Deal.

Given the general emphasis of the EU policy on the key role played by environmental innovation as the major source of a sustainable, equitable and fair society, there is a specific will to understand to what extent Member States are able to practically implement this development trajectory. Increasing attention is devoted to the role played by cross-country harmonization of policy instruments and convergence towards common targets, in order to better capture the double benefit of promoting sustainable transition while ensuring fair economic development for all EU Member States, also represented by the so-called Smart Specialization Strategy described in the Communication from the Commission on "Regional Policy contributing to smart growth in Europe 2020″ (COM(2010) 553 final).

To achieve higher sustainability standards, it is paramount to maximize opportunities from knowledge transfer of innovation developed across the EU, converging to a homogeneous and coordinated technological profile. Indeed, the fast evolution of the innovation trajectory requires all firms, sectors and regions to be equipped with the capacity to continuously upgrade their business and operational modes, by exploiting the potential associated to network relationships in finding new solutions or recombining existing knowledge assets (Balland et al., 2019). At the same time, contributions on the geography of transitions offer a common view that the spatial diffusion of environmental innovation is still highly heterogeneous, with few countries leading global transition processes (Losacker and Liefner, 2020).

We contribute to this debate by specifically evaluating if and to what extent EU countries are converging toward a homogenous eco-innovation dynamic pattern, to shed light on potential further opportunities to be exploited for maximizing the efficiency of EU policies directed towards sustainable transition. To this purpose, the performance of the EU Member States regarding the eco-innovation dynamics is measured by using the eco-innovation index, which comprises five thematic areas: eco-innovation inputs, eco-innovation activities, eco-innovation outputs, resource efficiency outcomes and socio-economic outcomes. The study of the overall index and its five dimensions allows us to identify convergence patterns not only in the aggregate measure, but also in the several areas behind the eco-innovation index, enriching the analysis and the potential policy recommendations in this field.

Thus, we rely on both the general index and its five thematic areas of eco-innovation, and we build a quantitative exercise to evaluate the convergence across countries in the EU. We apply the theoretical framework based on convergence clubs (Phillips and Sul, 2007, 2009) with the aim of finding clusters of EU Member States which share specific steady state positions, and potentially divergent countries. In addition, we carry out an ordered logit model to identify the drivers of the clusters for the general eco-innovation index to better understand the clubs endogenously achieved in the clustering procedure.

Despite the multiple perspectives developed by this kind of studies, few works are devoted to the convergence of eco-innovation at the country level. To the best of our knowledge, the club convergence approach has been employed to analyse different environmental variables in several contexts (e.g., Panopoulou and Pantelidis, 2009; Emir et al., 2019; Presno and Landajo, 2021; Presno et al., 2021; Delgado et al., 2022), but only Karman et al. (2020) analyse the absolute β-convergence for a sample of 38 countries in the period 2012–2017 specifically applied to eco-innovation. Hence, our analysis, under the lens of the current debate on the optimality of the policy mix design in improving the diffusion of best practices, enhancing economic performance and reducing the financial cost of the sustainable transition, contributes to the eco-innovation debate with two main novelties: i) we develop a convergence analysis of the eco-innovation index in the EU through the club convergence approach that allows to endogenously identify clusters from data; ii) we specifically investigate the determinants of such clusters through an additional ordered logit model.

[2] An interesting review of the drivers of eco-innovation can be found in Hojnik and Ruzzier (2016), and of eco-innovation in general in Díaz-García et al. (2015).

Table 1
Descriptive statistics – Eco-innovation index and its five dimensions.

	Eco-innovation index			Dim1-Inputs			Dim2-Activities		
	2012	2017	2021	2012	2017	2021	2012	2017	2021
Mean*	90.48	98.67	107.48	78.33	77.07	79.22	90.67	97.96	88.48
St. Dev.	30.91	31.13	30.89	52.29	46.30	43.69	34.31	29.08	31.54
C.V.	0.3416	0.3155	0.2874	0.6675	0.6008	0.5515	0.3784	0.2968	0.3564
Min.	31.00	34.00	50.00	1.00	1.00	5.00	38.00	51.00	34.00
Max.	149.00	157.00	171.00	211.00	184.00	154.00	162.00	149.00	152.00
Range	118.00	123.00	121.00	210.00	183.00	149.00	124.00	98.00	118.00
N. obs.	27	27	27	27	27	27	27	27	27
	Dim3-Outputs			Dim4-Resource efficiency			Dim5-Socio-economic		
	2012	2017	2021	2012	2017	2021	2012	2017	2021
Mean*	105.70	117.41	119.63	90.41	111.52	128.30	103.07	102.63	108.62
St. Dev.	44.37	49.81	43.99	54.02	59.12	64.40	53.92	52.90	53.14
C.V.	0.4198	0.4242	0.3677	0.5976	0.5301	0.5019	0.5232	0.5154	0.4892
Min.	27.00	26.00	24.00	2.00	6.00	17.00	23.00	24.00	29.00
Max.	197.00	223.00	210.00	244.00	250.00	268.00	234.00	234.00	234.00
Range	170.00	197.00	186.00	242.00	244.00	251.00	211.00	210.00	205.00
N. obs.	27	27	27	27	27	27	27	27	27

Source: European Commission and own elaboration.
* Unweighted.

The remainder of the paper is structured as follows. Section 2 describes the data and exposes the methodology based on the club convergence approach -first stage- and ordered logit -second stage-. Section 3 discusses the main results, while the conclusions are reported in Section 4.

2. Data and methodology

This section includes the data and descriptive statistics (with a preliminary sigma convergence analysis to explore the time evolution of the indicators), and the methodology applied in the study, including the club convergence approach and the ordered logit model.

2.1. Data and descriptive statistics

The eco-innovation index provided by the EU Eco-innovation Scoreboard measures environmental innovation with a composite indicator obtained by taking the unweighted average of 16 variables which are classified into five thematic areas or dimensions, each of them measured through three or four indicators :[3]

1. Eco-innovation inputs include investments (financial or human resources) that provide an initiative for eco-innovation activities at companies, research organisations and other institutions. Specifically, this dimension includes:
- Government environmental and energy R&D appropriations and outlays
- Total R&D personnel and researchers
- Total value of green early-stage investments
2. Eco-innovation activities focus on efforts and activities towards developing new or improved products and services, changing business models and introducing eco-management in companies or organisations:
- Implementation of resource efficiency actions among Small and Medium Enterprises (SMEs)
- Implementation of sustainable products among SMEs
- Number of ISO 14001 certificates
3. Eco-innovation outputs comprise the immediate results of eco-innovation activities (knowledge outputs generated by businesses and researchers related to eco-innovation):
- Eco-innovation related patents
- Eco-innovation related academic publications
- Eco-innovation related media coverage
4. Resource efficiency outcomes are related to attaining a low-carbon and resource efficient Europe through increasing the resource efficiency performance of sectors and countries. Eco-innovation can have a double positive impact on resource efficiency: increase

[3] For more details, see https://ec.europa.eu/environment/ecoap/indicators/index_en. Early efforts in measuring eco-innovation can be found in Arundel and Kemp (2009).

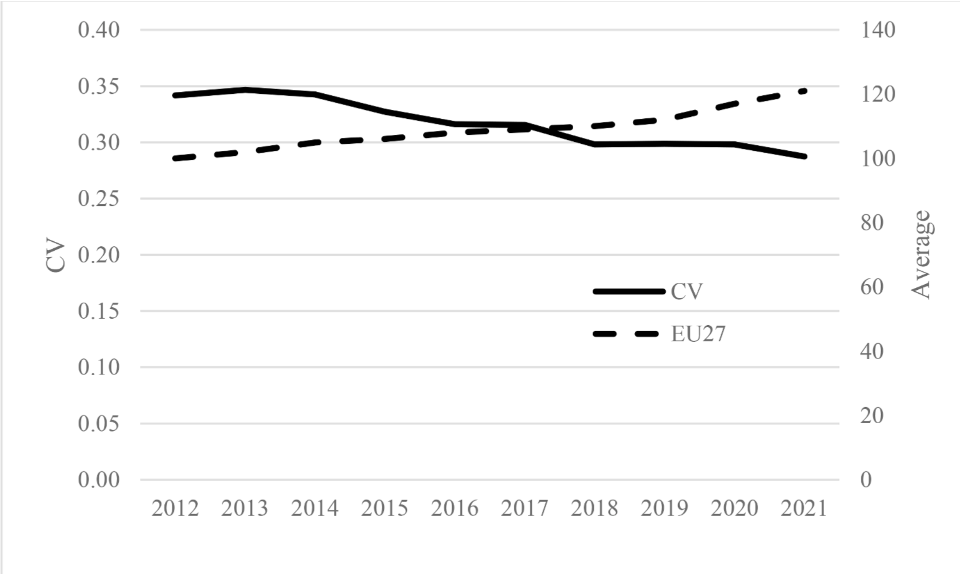


Fig. 1. Sigma convergence and average of eco-innovation index.

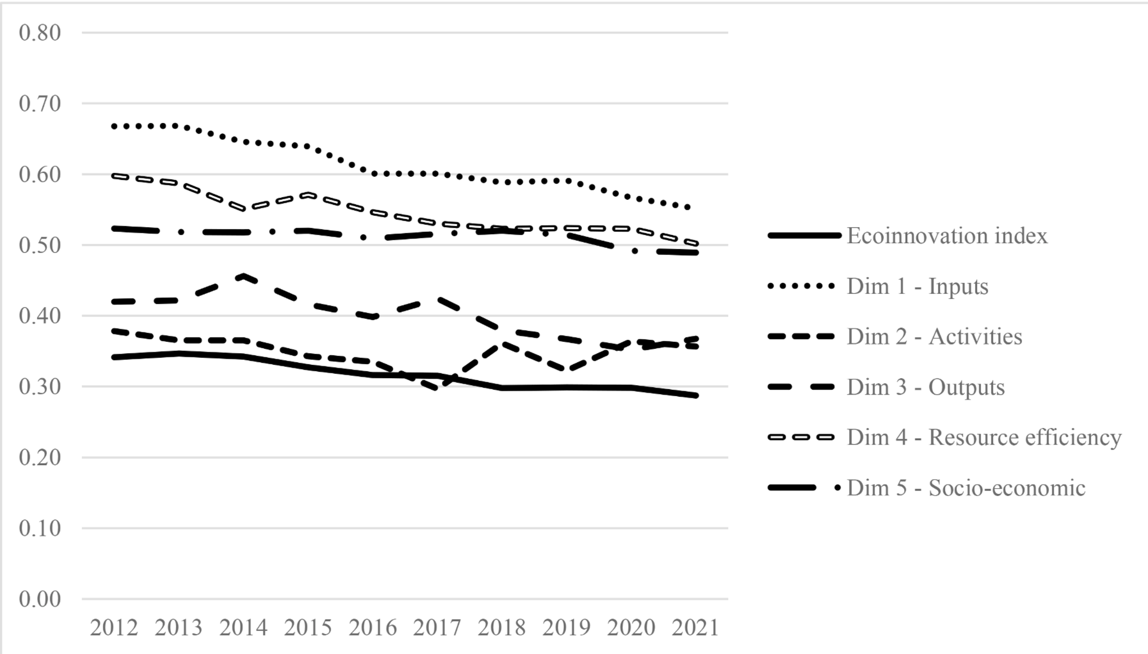


Fig. 2. Sigma convergence of the five dimensions of eco-innovation index .

the generated economic value and decrease pressures on the natural environment. This thematic area creates a link between the adoption of eco-innovation with resource saving and environmental impacts:
- Material productivity
- Water productivity (GDP/total fresh water extraction ratio)
- Energy productivity
- GHG emissions productivity
5. Socio-economic outcomes include effects of eco-innovation activities for society and the economy (e.g., changes in employment, competitiveness, exports, revenues, company profits and expenses):
- Exports of environmental goods and service sectors

- Employment in environmental protection and resource management activities
- Value added in environmental protection and resource management activities

We analyse the 27 Member States of the EU (excluding the UK) and the available sample covers the period 2012–2021. Table A1 in Annex A reports the precise ranking, for both the general eco-innovation index and its five dimensions in the initial and the final period of the sample, 2012 and 2021 respectively.[4] Although in different order, Denmark, Finland and Luxembourg maintain the first three positions in 2012 and 2021. In the other extreme, Bulgaria and Poland present the lowest indexes in both years.

Table 1 contains the descriptive statistics of the general eco-innovation index and the five dimensions for the three years out of the sample, namely 2012–2017–2021. In the selected years, Bulgaria presents the lowest indicator, and Luxembourg reaches the highest index in the most recent years. Additionally, as preliminary analysis, we have performed a sigma convergence analysis through the coefficient of variation (CV), reported in Fig. 1. We observe the continuous increase in the average, accompanied by a reduction in the CV, denoting a sigma convergence pattern of eco-innovation across EU countries in the period. However, this process is not uniform across dimensions (see Fig. 2). The sigma convergence is more pronounced in dimensions 1 (eco-innovation inputs) with a decline of 17.38% in the CV, 4 (resource efficiency outcomes) with a drop of 16%, and 3 (eco-innovation outputs) descending by 12.40% in the period 2012–2021. Moreover, the club convergence approach will be very useful to better understand the dynamics of the eco-innovation beyond this aggregate time evolution.

2.2. Methodology

Along with the multiple interpretations and empirical assessments of the relation between regulatory policy in environmental domains and the related impact on the economic structure, including the development of new and cleaner technological trajectories, a general framework of interpretation can be traced back in the original formulation of the so-called Porter Hypothesis (PH), initially proposed in the seminal paper by Porter and van der Linde (1995), further expanded at the theoretical and empirical level by Jaffe and Palmer (1997), and finally assessed in its validity after two decades by Ambec et al. (2013).

Indeed, while innovation and economic performance are interlinked features of the original PH at the domestic level, there is a growing interest among scholars and policy experts around issues related to policy coordination and cross-country influence that are equally important for the competitive outcomes of the sustainable transition. Following Costantini et al. (2022), the instruments forming the policy mix within each country together with the policy space across EU member states are both elements that jointly influence how market regulation, required for the achievement of environmental targets, might reinforce the benefits in terms of economic competitiveness and growth. In this analysed case of energy efficient technologies for the residential sector, the convergence toward a common EU sustainable energy transition process seems to speed up such a transition in all member states. However, those economies lagging behind are at risk of losing the opportunity of being on track of the sustainable transition pathway, not only reducing their own market opportunities but also causing a potential loss for the whole EU, due to the violation of the cost effectiveness of public investments.

Given the existence of such multiple forces at work that should be included and empirically measured to assess the effective changes occurring at the domestic level in EU countries, also accounting for the cross-country mutual influence, a systemic approach is a valuable solution to develop the empirical strategy. The complex, evolving and uncertain nature of the dynamics at play makes it necessary that the analysis of a sustainability transition accounts for the multi-level agents that mobilise knowledge, entrepreneurial activities, and technology development (Hekkert et al., 2007). Indeed, while the definition of the general target of a large-scale transition is a typical top-down process, the actual implementation involves coordination across multiple stakeholders and related behaviours (Grubler, 2012). Barriers and frictions occurring along the process due to misalignment of preferences across these multiple agents (belonging to different countries) might create winners and losers. In other words, it could be a process characterised by more or less converging clusters of countries, with a risk of the formation of clubs and a reduction in those latent benefits from cross-country coordination. This implies that whatever the analysis of environmental regulation carried out in the EU context, it cannot overlook the potential of cross-country knowledge and/or policy spillovers in broadening the impact of domestic policies (Fabrizi et al., 2018).

In line with the aforementioned debate, in this empirical analysis we evaluate the existence of a convergence pattern in the eco-innovation process by applying the methodology developed by Phillips and Sul (2007, 2009) to a panel of countries consisting of the EU27 Member States. In doing so, it is possible to empirically build a classification of countries into convergence groups or clubs by the application of the "log *t*" test. Moreover, given the complexity of the policy process under investigation, we follow the suggestion of adopting a systemic approach when measuring the eco-innovation performance, in order to jointly include as many aspects as possible of the multiple agent interactions and cross-country influence.

Both the Phillips and Sul approach and the sigma convergence analysis (implemented in the previous subsection), share the common feature of focusing on the evolution over time of the cross-sectional dispersion indicator. However, unlike the sigma convergence approach, the Phillips and Sul proposal is based on a panel data model with both common and individual specific components formulated as a non-linear time-varying factor model, with the additional feature that it does not impose any particular assumption concerning the time properties of the variables. This resulted in a model which represents the behaviour of economies in transition and allows for a broad variety of time paths, and also in a test which leads to the detection of clubs of convergence.

[4] Original data are available upon request.

Formally, we consider as the dependent variable y_{it} the eco-innovation index - or each dimension - with $i = 1,\ldots, N$ and $t = 1,\ldots,T$, where N represents the number of countries and T the number of years. Following Phillips and Sul (2007), the dependent variable can be decomposed as:

$$y_{it} = \delta_{it}\mu_t \tag{1}$$

where μ_t represents the common component and δ_{it} is the idiosyncratic component that measures the individual economic distance between the common trend component and y_{it}.

The common factor in (1), μ_t, may be removed by scaling to give the relative transition coefficients:

$$h_{it} = \frac{y_{it}}{N^{-1}\sum_{i=1}^{N} y_{it}} = \frac{\delta_{it}}{N^{-1}\sum_{i=1}^{N}\delta_{it}} \tag{2}$$

h_{it} is the "relative transition path" in the sense that it traces an individual trajectory over time for country i relative to the cross-section average,[5] and can be considered to be economy i's relative departure from μ_t, reflecting possible divergences from it.

Under convergence, h_{it} converges to unity, and the cross-sectional variance of h_{it}: $H_t = N^{-1}\sum_{i=1}^{N}(h_{it}-1)^2$, converges to zero asymptotically.

From these properties, the "log t" convergence test is based on running an OLS estimation with a robust covariance matrix:

$$\log\left(\frac{H_1}{H_t}\right) - 2\log(\log(t)) = \alpha + \gamma \log(t) + u_t \tag{3}$$

for $t=[rT]$, $[rT]+1$, …, T, where $r = 0.3$ for sample sizes below $T = 50$, and $[rT]$ represents the integer part of rt (Phillips and Sul, 2009). Finally, $-2\log(\log(t))$ is a penalization function which improves the performance of the "log t" convergence test.

The fitted coefficient on "log t" regression is $\widehat{\gamma} = 2\widehat{\alpha}$, where $\widehat{\alpha}$ is the estimate of the speed of convergence, and the null of convergence can be tested through a one-sided t-test of the null $\gamma \geq 0$, which is rejected at 5% significance when $t_{\widehat{\gamma}} < -1.65$.

Also, the procedure allows us to conclude the existence of conditional convergence (i.e., convergence in growth rates) when $0 \leq \widehat{\gamma} < 2$, $0 \leq \widehat{\alpha} < 1$; and absolute convergence (i.e., convergence in levels) for $\widehat{\gamma} \geq 2$, $\widehat{\alpha} \geq 1$.

When the null of convergence is rejected for the whole panel, a four-step clustering algorithm based on the application of the "log t" regression allows to endogenously identify clubs of convergence (Phillips and Sul, 2007).

The "log t" regression also allows us to explore the possible mergers among clubs and to study evidence of convergence between neighbouring members of different clubs. In this regard, Phillips and Sul (2009) conclude that, when T is small, as in our case, the procedure tends to increase the chance of finding more convergence clubs than the true number due to its conservative nature. With the aim of avoiding this overdetermination, they propose the application of the "log t" regression to conclude whether any of the original clubs can be merged and form larger convergence clubs. In addition, the procedure allows to examine the evidence of transitions between adjacent clubs (i.e., clubs that slowly converge to one another, or specific countries in a club with a tendency to be in transition towards a contiguous group). For that, the "log t" test is run for 50 per cent of the lowest (in terms of eco-innovation index) members in the upper club and for 50 per cent of the highest (again in terms of eco-innovation index) states in the lower club.

Once the convergence clubs are obtained, our analysis addresses the research of the explanatory factors of eco-innovation club membership. Based on the characteristic (an ordinal outcome) of the dependent variable, we estimate an ordered logit model (McKelvey and Zavoina, 1975).

The model is expressed as:

$$y_i^* = X_i\beta + \varepsilon_i \tag{4}$$

where y_i^* represents the latent variable which takes ordinal values; i refers to the country ($i = 1,\ldots,27$); X_i is the set of independent variables; the vector β contains the regression coefficients, and ε_i is the random disturbance term which has a standard logistic distribution.

3. Results: club convergence analysis and drivers of clusters

3.1. Club convergence of the eco-innovation index

The results relative to the total eco-innovation index are displayed in Table 2. The null of convergence for the whole set of EU countries is rejected at the 5% level, but the "log t" test allows the identification of some convergence clubs. This means that the 27 countries are still far from being entirely coordinated in the implementation of regulatory policies designed to achieve a common eco-innovation standard.

At the same time, there are convergence patterns around common development strategies at least for selected countries. By

[5] In Section 3, Figures 3 and 4 show the relative transition paths corresponding to clubs obtained for the eco-innovation index and its five dimensions, respectively.

Table 2
Convergence club results. Eco-innovation index.

Initial Clubs	Countries	$t_{\widehat{b}}$	$\widehat{b}(s.e.)$	Merge	Final Clubs	Countries	$t_{\widehat{b}}$	$\widehat{b}(s.e.)$	Type[+]
Full sample		−25.893	−0.603 (0.023)						
Club 1	LU, FI, DE, SI	1.309	0.264 (0.202)	Club 1 + 2 + 3 + 4+ES	Club I	LU, FI, DK, AT, SE, DE, FR, ES, IT, NL, PT, SI, CZ, IE, BE, EL	0.319	0.061 (0.191)	High
Club 2	DK, AT, IT, NL, EL	0.613	0. 209 (0.341)		Club II	EE, LV, LT, HR, SK, CY, BG	0.865	0.034 (0.191)	Med
Club 3	SE, FR, IE	0.303	0.027 (0.091)		Club III	RO, HU, MT, PL	2.899	2.032 (0.701)	Low
Club 4	PT, CZ, BE	0.077	0.026 (0.338)						
Club 5	EE, LV, LT, HR, SK, CY, BG	0.865	0.034 (0.191)						
Club 6	RO, HU, MT, PL	2.899	2.032 (0.701)						
Divergent	ES								

Belgium (BE), Bulgaria (BG), Czech Republic (CZ), Denmark (DK), Germany (DE), Estonia (EE), Ireland (IE), Greece (EL), Spain (ES), France (FR), Croatia (HR), Italy (IT), Cyprus (CY), Latvia (LV), Lithuania (LT), Luxembourg (LU), Hungary (HU), Malta (MT), Netherlands (NL), Austria (AT), Poland (PL), Portugal (PT), Romania (RO), Slovenia (SI), Slovakia (SK), Finland (FI), Sweden (SE).
Source: own elaboration.

* Indicates rejection of the null hypothesis of convergence at the 5% level.

[+] This is merely a relative denomination to differentiate the clubs according with their average data.

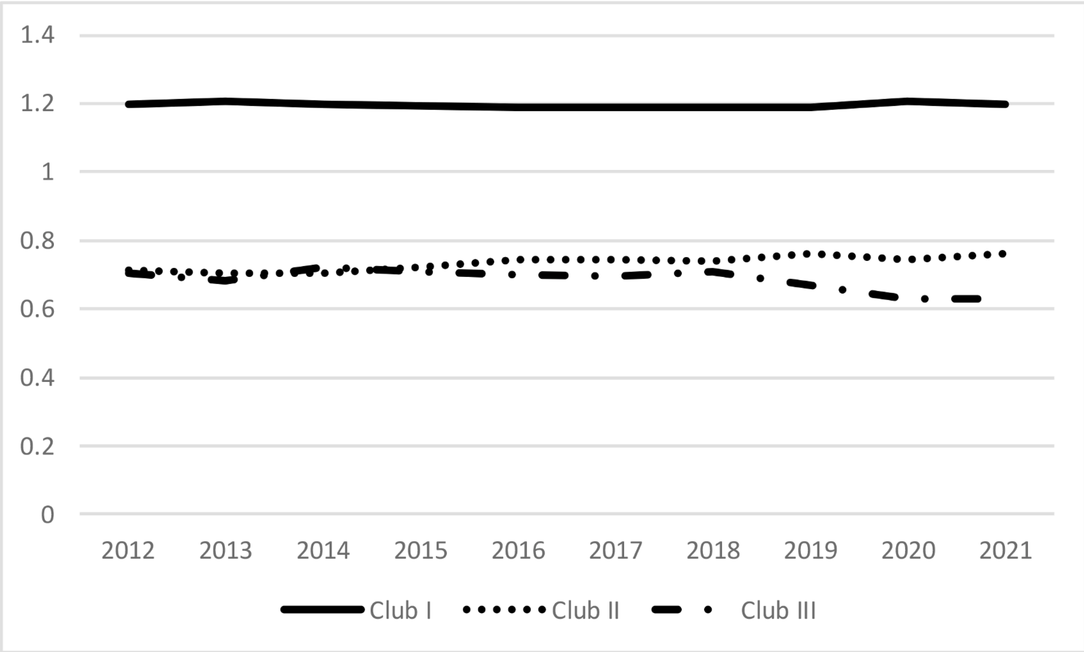


Fig. 3. Transition curves – Eco-innovation index after merging, 2012–2021 .

examining the empirical results in depth, it emerges that initially, six clubs plus a divergent country, Spain, are detected. It is also highlighted that, with the exception of Club 6, conditional convergence is found, i.e., convergence in growth rates, and not in levels. However, the absolute convergence of Club 6 implies that Hungary, Malta, Poland and Romania converge to a club-specific eco-innovation level in the period under study.

The implementation of the merger procedure (commented previously) in our primary results leads to join Clubs 1, 2, 3, 4 and Spain, forming Club I, which displays conditional convergence and a low speed of convergence.

We also analysed the possible union of the two remaining clubs (5 plus 6), obtaining $t_{\hat{b}} = -1.469$, which would lead to a very weak club of convergence. Thus, we finally opted for considering three convergence clubs: Clubs I, II and III (see Table 2). Starting from this base result, it is worth mentioning that on the basis of a general quantification of the eco-innovation performance of a country, at the EU level there are still countries lagging behind in the coordinated structure of deployment and diffusion of clean technologies and environmental-friendly standards and managerial procedures. In particular, while in Club I we can see countries belonging to the first wave of formation of the EU after the transformation of the common market, in the other two Clubs countries belonging to the ensuing enlargement waves are located.

Fig. 3 displays the transition paths corresponding to the clubs. Club I shows a transition path above 1, and includes the group of long-time EU Member States, plus two more recent Central/Eastern members (the Czech Republic and Slovenia). By contrast, Clubs II and III exhibit transition paths below 1, and include recent Central/Eastern Members plus two islands: Cyprus and Malta. Both clubs present similar transition paths for part of the sample, although they tend to separate for the last few years.

Regarding the analysis of transitions between adjacent clubs, our results put the evidence on a transition between Club II and Club III, with a statistic $t_{\hat{b}} = 1.669$.

The results on the transitions between clubs, or of specific countries from one club to another, reflect the uncertain condition of some Members in closing the technological gap. This is a further confirmation of what is found in several cluster-based analyses applied to different domains. At the general level, following Costantini and Crespi (2015), one reason behind the clustering process and the transition through different clubs especially for Central and Eastern European countries can be traced back in the network of bilateral trade relationships, together with the common language that can facilitate common patterns of development. This is particularly relevant in the case of technology development and deployment actions in environmental-friendly domains, since the exchange in knowledge capabilities at the bilateral level is also affected by the specific web of linkages in the network of innovation dynamics (Costantini et al., 2022).

3.2. *Club convergence of eco-innovation dimensions*

With the purpose of deepening the analysis of the process of convergence in eco-innovation in the EU, we extend the study of convergence to the five dimensions or thematic areas forming the synthetic index with the aim of revealing if and to what extent specific country or club characteristics might better inform the policy debate upon how to enhance the general convergence. For all

Table 3
Convergence club results. Dimensions (summary) .

Dimension	Clubs	Countries
1 Eco-innovation inputs	I	DE, FI, SE, SI, LU, DK, NL, FR, EL, BE, AT, CZ, IT, ES, IE, HU, HR
	II	PT, EE, LT, LV, BG
	III	SK, PL
	IV	RO, MT, CY
2 Eco-innovation activities	I	SE, ES, IE, SI
	II	CZ, PT, FR, IT, DK, CY
	III	AT, HR, FI, BE, LU, DE, NL, SK
	IV	HU, MT, LV, PL, EL, EE, BG
	V	LT, RO
3 Eco-innovation outputs	I	DK, FI, SE, LU, DE, EE
	II	AT, NL, BE, CY, PT
	III	IE, FR, LV, SI, EL, IT, ES, LT, CZ, PL, HR, SK, RO, BG
	IV	HU, MT
4 Resource efficiency outcomes	I	IT, LU, MT, BE, NL, IE, DE, FR, CZ, LT
	II	SK, DK, ES, LV, AT, HR, SE
	III	CY, SI, EL, PL
	IV	PT, HU, RO, FI, EE, BG
5 Socio-economic outcomes	I	FI, AT, EE
	II	DK, LU
	III	RO, LV, PT, LT, CZ, EL, SI, NL, DE, SK, FR
	IV	CY, ES, SE, HR, IT, PL, BG, IE
	V	MT, BE

Source: own elaboration.
Note: in dimension 5, Hungary is not included due to the absence of data for the entire period. Results correspond to clubs after merging procedure.

dimensions the null of convergence is rejected, and Table 3 summarises the countries which compound the different clubs, right after the merger,[6] in each thematic area. In the same way, Fig. 4 displays the transition paths for the different dimensions.

Not surprisingly, the dimension-disaggregated analysis allows to highlight that, countries positioned for the overall eco-innovation index in the club whose transition path is above 1 (Club I), also, in most dimensions, belong to the club whose transition path is also above 1. The same behaviour is observed in countries belonging to Clubs II and III, also classified for most dimensions in clubs with transition paths below 1. The position of the club transition path relative to value 1 differs between the overall eco-innovation index and the dimensions just for the following countries and dimensions:

- Dimension 1 (eco-innovation inputs): Portugal (below 1), Croatia and Hungary (above 1).
- Dimension 2 (eco-innovation activities): Greece (below 1); Croatia (above 1).
- Dimension 3 (eco-innovation outputs): Slovenia, Italy, Greece, the Czech Republic and Spain (below 1); Cyprus and Estonia (above 1).
- Dimension 4 (resource efficiency outcomes): Finland, Slovenia, Greece and Portugal (below 1); Latvia, Lithuania, Croatia and Malta (above 1).
- Dimension 5 (socio-economic outcomes): Italy, Sweden, Ireland, Belgium and Spain (below 1); Estonia, Latvia, Lithuania and Romania (above 1).

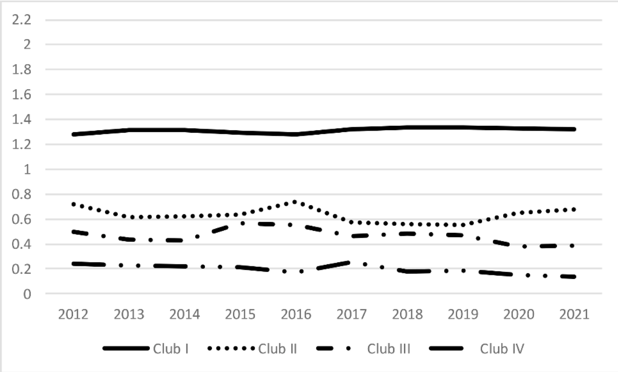
Interestingly, in the first two dimensions which refer to efforts, investments and activities, in order to attain the development of eco-innovation, only countries whose transition path changes above or below the mean of the EU are selected, depending if we focus on the overall eco-innovation index or on the specific dimensions. However, these changes become more frequent for dimensions which refer to outcomes: eco-innovation outputs, resource efficiency and socio-economic outputs.

Focusing on countries belonging to Club I, most leading countries in eco-innovation (namely Austria, Denmark, France, Germany, Luxembourg, and the Netherlands) converge to clubs whose transition path outperforms 1 for all the dimensions. Two exceptions are Finland and Sweden. Although Finland is a leading nation in the field of eco-innovation, its performance in the resource efficiency dimension is relatively low, mainly as a consequence of a low energy, water and material productivity. On the other hand, the Achilles' heel in the case of Sweden, another leader in eco-innovation in the EU, is the socio-economic outcomes dimension, mainly due to the component related to employment in eco-industries. Other countries within this Club I with significant shortcomings in socio-economic outcomes are Belgium and Ireland.

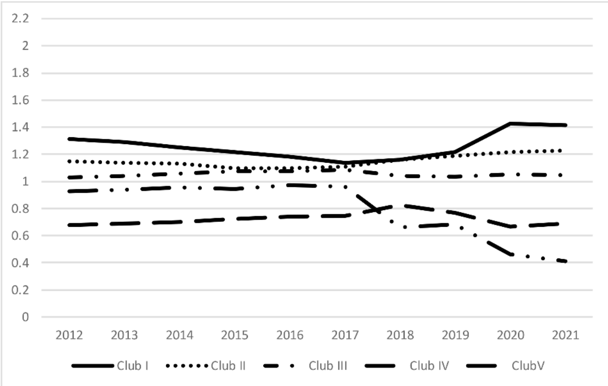
To conclude with countries in Club I, the cases of Spain and Italy can be highlighted: both economies are positioned in similar clubs for all the dimensions, and both converge to clubs under 1 for outputs, mainly due to the low development of patents related to eco-innovation and socio-economic outcomes. This result can be interpreted as a general confirmation of what Costantini et al. (2020) found for the energy efficiency development and deployment in the residential sector. Indeed, a variety of factors drive eco-innovation,

[6] Detailed primary results -before merging- are available from authors upon request.

4.1. Dimension 1. Eco-innovation inputs



4.2. Dimension 2. Eco-innovation activities



4.3. Dimension 3. Eco-innovation outputs

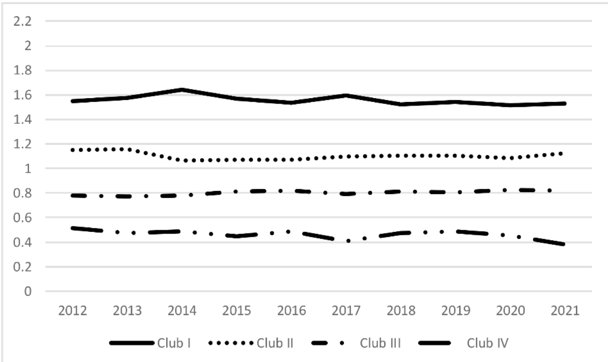


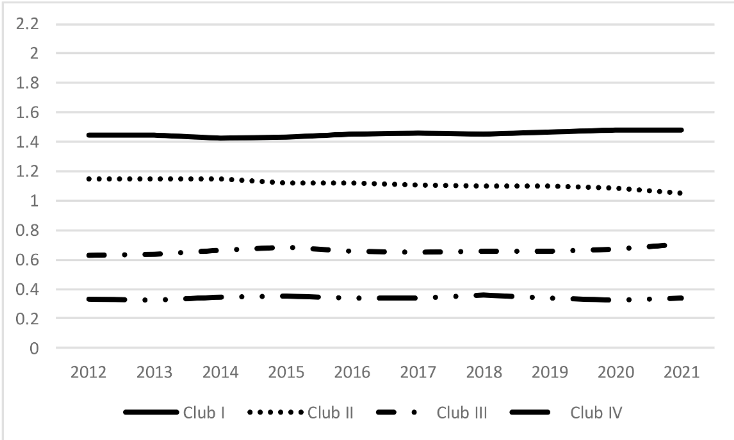
Fig. 4. Transition curves for the five eco-innovation dimensions .

including public regulation (Veugelers, 2012), investments in technological capabilities and knowledge diffusion, good institutions, and cooperation (Ghisetti et al., 2015). Accordingly, the differences between countries in such aspects, well represented by the single dimensions of the synthetic eco-innovation index, are still conflicting with the effective implementation of a convergence process, despite the huge financial and institutional efforts made by the EU.

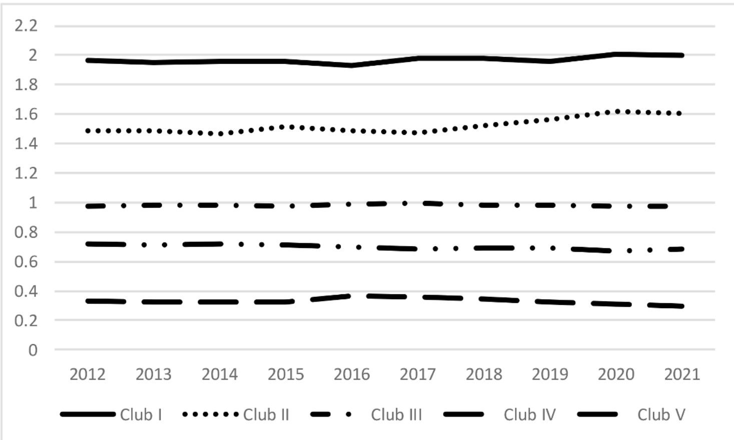
Turning now to countries in Clubs II and III, at the bottom of the eco-innovation index for the period under investigation, we find Bulgaria and Poland, two countries which underperform in all the dimensions. On the other hand, the Baltic States of Estonia, Latvia and Lithuania exhibit as common denominator their convergence to high-convergence clubs for socio-economic outcomes, employment and turnover in eco-industries being two driving forces in this field. Additionally, Latvia and Lithuania stand out in resource efficiency outcomes as a consequence of results in water productivity. Other countries well positioned in this dimension largely due to water productivity are Malta and, to a lesser extent, Croatia. Finally, Romania converges to an outstanding club in socio-economic outcomes because of the positive evolution of employment and turnover in eco-industries.

Also, in this case our results provide the general confirmation of previous findings, such as for instance those reported by Horbach

4.4. Dimension 4. Resource efficiency outcomes



4.5. Dimension 5. Socio-economic outcomes



Source: own elaboration

Fig. 4. (*continued*).

(2016) with a firm-based analysis. Along with the reduced convergence on eco-innovation, and the clustering of early EU Members in common clubs, our analysis confirms that on average the Eastern EU countries are still less eco-innovative compared to the other EU countries, both in terms of supply and demand. The dimensions mainly driving this gap are those related to the eco-innovation inputs and the socio-economic outcomes, as the divergence across the different clubs is higher, leading to further examine the specific differences and divergence occurring at the dimension level.

3.3. Factors behind the clusters

Once endogenously identified the clusters with the club convergence procedure, we look for the determinants of such clubs for the overall eco-innovation index through an ordered logit model.

The wealth of literature on eco-innovation focuses on several dimensions both at the firm or sector level (Liao and Liu, 2021), and at a more general country level, depending on the specific research hypothesis under investigation, providing several insights to guide the choice for driving factors to be used in the econometric estimation. In particular, according to the strand of contributions working on the general concept of policy mix design, the determinants of eco-innovation can be grouped into four categories (Horbach et al., 2012; Peters et al., 2012; Rogge and Reichardt, 2016; Costantini et al., 2017): market-based elements, divided into demand-pull and technology-push, regulatory push/pull factors, voluntary and soft instruments, and finally country and firm-specific socio-technical features.

While there is a consensus at the EU level that market-based instruments are positive elements in directing eco-innovation performance (Costantini et al., 2020), there is still an open debate regarding the specific features impacting firms' behaviour (Del Rìo *et al.*, 2017). By looking at firm-based analyses applied to specific countries, for instance in the Spanish case, Cuerva et al. (2014) find that

Table 4
Ordered logit model results.

Variable	Estimation
GDPpc	−0.00021** (−2.167)
R&D	−0.69480 (−0.6387)
EnvTaxPerc	−0.01941 (−0.0534)
Openness	0.02246** (1.9660)
FirmSize	0.28711 (0.8917)
Number and percentage of corrected cases	21 and 77.8%
Chi-squared and p-value	26.8733 and 0.0001
Brant test – Chi-squared and p-value	0.00 and 1.00
Obs	27

Source: own elaboration; z-value between parentheses; **: significant at 5%.

the higher implementation of voluntary scheme certifications such as Quality Management Systems (QMS) is more effective to enhance eco-innovation than public subsidies. In the same vein, García-Granero *et al.* (2020) analyse the role of environmental corporate culture and commercial orientation, concluding clear links with eco-innovation.

Turning to cross-countries firm-based analyses, according to Triguero et al. (2013) supply-side, demand-side and regulatory factors are key determinants for the eco-innovation trajectory of Small and Medium Enterprises (SMEs). Similarly, Horbach (2016) analyses the determinants of eco-innovation for 19 European countries and sectors using data from the Community Innovation Survey (CIS), showing that regulation is crucial for the development of eco-innovative trajectories especially in traditional highly-polluting sectors. Furthermore, this dependence on regulation and subsidies is particularly evident in Eastern European countries, where domestic technological capabilities are still far from converging towards the EU average standards.

It should be noted that in our convergence analysis we use as a measure of eco-innovation a composite index already formed by five dimensions. Accordingly, the explanatory variables driving the eco-innovation clustering process in the ordered logit should be selected with a parsimonious approach, in order to minimize potential endogeneity biases. To this end, we rely on the contributions by Păcesilă and Ciocoiu (2017) and Zubeltzu-Jaka et al. (2018), as a good synthesis of the main drivers from the literature review, and we select five determinants: i) the GDP per capita as a general economic dimension; ii) the R&D investments as a percentage of GDP, representing the technology-push market-based dimension; iii) the environmental tax revenue as a percentage of total tax revenue, measuring the demand-pull market-based dimension; iv) the relative dimension of trade with respect to GDP, as a measure of the absorptive capacity of external spillovers; and v) the average firm size as a specific characteristic of the business environment, also measuring the capacity to attract investments by firms.[7]

Considering the number of the club to which each country belongs in the convergence analysis of countries as the dependent variable, the ordered logit model includes the explanatory variables here selected as average values of available data for the period 2012–2021 in the estimation. Regarding the expected signs, it should be taken into account that 1 (Club I) corresponds to the highest eco-innovation level, while 3 (Club III) indicates the lowest level, implying an inverse interpretation of the signs: a negative sign in the estimation is associated with a positive relationship or effect with eco-innovation, and vice versa, so we must address this contradiction between expected sign and expected effect.

- GDPpc: GDP per capita. Expected effect: positive (expected sign: negative). Our hypothesis is that the higher the per capita income of a country, the higher its level of development and interest for innovation and also for environmental protection and, hence, for eco-innovation.
- R&D: R&D investment as a percentage of GDP. Expected effect: positive (expected sign: negative). Countries with higher R&D expenditures also have a larger likelihood of activating positive outcomes related to eco-innovative solutions.
- EnvTax: environmental taxation as a percentage of total tax revenues.[8] Expected effect: undefined. Environmental taxation could boost eco-innovation activities but also slow down this agenda, and the combined effect is not predictable a priori.
- Openness: degree of economic openness, measured as the sum of exports and imports as a percentage of GDP. Expected effect: undefined. Higher trade activities are expected to contribute to local innovations if the domestic economy is able to absorb the potential benefits of trade, but if the national economy is unable to properly stimulate the domestic economic activities, a higher proportion of trade values to the GDP can be harmful to domestic innovation (Canh et al., 2019). This uncertain prediction can be extended to eco-innovation, with due caution.
- FirmSize: proportion of firms of 10 or more employees. Expected effect: positive (expected sign: negative). A high proportion of companies[9] of a certain size should be associated with higher levels of innovation in general, and of environmental innovation, in particular.

[7] As a robustness check, we have estimated the model including the Corruption Perception Index elaborated by Transparency International as a measure of the institutional capability. However, being non-significant, we have decided to exclude it from the reported results.

[8] Alternatively, we have also estimated the model with EnvTaxGDP - Environmental taxation as a percentage of GDP -, with similar results.

[9] In a related and interesting way, Cheng et al. (2014) analyse the relationship between eco-innovation and business performance for Taiwan, concluding a strong effect of eco-organizational innovation.

The main results of the ordered logit regression are reported in Table 4,[10]including the Brant test regarding the parallel lines assumption, which is not violated. Among the five factors theoretically influencing the eco-innovation patterns and related convergence in clubs, we find only two significant effects related to the GDP per capita and the degree of openness to international trade. These two factors together allow reaching 77.8% of correctly predicted cases in the model, revealing that the model fitness is reliable. The negative sign of the variable GDP per capita as already mentioned should be interpreted here as a positive effect, meaning that countries with higher and more diffused opportunities among the whole population are converging rapidly to high standards of eco-innovation. Conversely, a high degree of economic openness, with a positive sign, is associated with a reduction in the convergence toward a high level of eco-innovation. Thus, our results indicate that, on average, higher trade activities are counter effective in contributing to domestic eco-innovation performance. This specific result can be explained under the lens of the relative specialisation pattern in the supply chain of products embedding technological innovation with a specific pro-environmental purpose. Those countries that benefit from large flows of exports and imports, including intermediate inputs, can exploit the technological content of traded goods without spending large amounts of financial resources to develop new and cleaner technological devices. To some extent, this is what has been demonstrated specifically for the energy efficiency sector by Costantini et al. (2020), where the large trade flows between Germany and the Eastern European partners (especially Poland) have improved the economic competitiveness of the trading partners in the whole EU market without a proportional increase in the efforts for the development of energy efficient technologies.

Quite interestingly, the other three factors theoretically chosen for their influence on eco-innovation dynamics from previous studies are not statistically significant in ordering the degree of convergence in high eco-innovative performances. One potential explanation behind this specific result is that in most cases the empirical studies are carried out at the firm or sector level, while in this case the unit of analysis is the country level. Future research on this specific aspect could be conducted, applying this methodology to micro or *meso* level data if available.

3.4. Discussion

Our analysis provides evidence on the emergence of three clubs of convergence for the overall eco-innovation index, denoting common patterns across EU countries during recent years. This convergence process is more heterogeneous at the dimensions level, since the number of clusters ranges between four and five when different dimensions are analysed, with the largest heterogeneity envisaged in eco-innovation activities and eco-innovation socio-economic outcomes.

To contextualize the possible causes of policy convergence in general, following Busch and Jörgens (2005), there are at least three classes of mechanisms: the co-operative harmonization of domestic practices, through international legal agreements or supranational law, the EU being a clear example of this channel in several areas; the coercive imposition of political practices, by economic, political or military threat, intervention or conditionality; and the diffusion of practices, through cross-national imitation, emulation or learning. It should be noted that the EU policy-makers have attempted to promote eco-innovation through the implementation of ambitious programmes such as Horizon 2020, the European Green Deal and the Next Generation EU. However, the great differences between EU countries, in terms of GDP, production mix or R&D expenditure, complicate a possible overall convergence on this common pathway. Eco-innovation is a very complex process that involves several dimensions: product, process, organizational and marketing, among others. Despite these efforts, we basically agree with Colombo et al. (2019) in pointing out that eco-innovation is to some extent a buzzword and there is still space for improving the circular economy discourse to boost economic growth and sustainability.

Undoubtedly, this study of convergence of eco-innovation must also be analysed in the context of convergence of environmental policy and of innovation dynamics in the EU. Regarding the first issue, Liefferink and Jordan (2005) address the convergence of 10 national environmental policies, with mixed results denoting that the “Europeanization” process cannot be defined as a fast, smooth or self-perpetuating process of convergence in the EU. In the same vein, Strunz et al. (2018) study the case of EU renewable energy policies, concluding that there is a temporary convergence in the case of policy support instrument choices, but an evident divergence in public R&D subsidies targeting renewables. Furthermore, Delgado et al. (2022) specifically analyse the convergence of environmental taxation, revealing a high degree of convergence of the total environmental taxation and its two main subcategories, energy and transport taxes.

With regard to the second issue, Archibugi and Filippetti (2011) explore the convergence of innovation in EU countries for 2004–2008, concluding that there is a clear convergence in technological capabilities and innovation performance. Nonetheless, according to Barrios et al. (2019) this convergence process appears more heterogeneous when a sub-national approach is adopted, since seven convergence clubs for innovation development emerge at the regional level. The existence of regions still lagging behind the technological upgrade process can be explained by the strong divide in the efforts played by countries in knowledge creating investments, as revealed by Blanco et al. (2020) in their analysis of convergence of R&D expenditures, with a significant divide between the outperforming group of long-lasting EU Member States and the lagging behind cluster formed by newcomers.

Our results in eco-innovation are certainly in line with those achieved both for the environmental policy and for the convergence of innovation, with common patterns during the last few years. In addition, along with recent findings by Consoli et al. (2023), these

[10] Following the suggestion raised by one of the referees, in addition to this analysis with the average values of the entire period for the explanatory variables, we have also estimated the ordered logit model considering the explanatory variables splitting the sample into two periods. The results of the ordered logit models are similar, with the same significant variables and practically equal coefficients. Detailed results are available upon request.

results invite policy makers to promote eco-innovation to a greater extent, seeking more powerful instruments to enhance innovation and environment protection simultaneously. The degradation of the environment and the general benefits from innovation deserve a determined push of eco-innovation, and this boost must be accomplished by all countries to reach the pursued objectives.

4. Concluding remarks

Eco-innovation has become a central element in the EU during recent years, and it is clearly reflected in several instruments and programmes, including Horizon 2020 and its update, Horizon Europe, the European Green Deal or the recent Next Generation Fund.

The eco-innovation index provided by the European Commission is an interesting composite indicator that allows comparing the evolution of eco-innovation patterns across EU countries, and understanding the dynamics of the convergence process. According to our results, the sigma convergence analysis shows evidence of such approximation in this period, in the total eco-innovation index and the five dimensions, although the dynamics are different, being more intense in dimensions related to the adoption of eco-innovation inputs, the resource efficiency outcomes and the eco-innovation outputs. On the other hand, with respect to the three dimensions of eco-innovation activities, inputs and socio-economic outcomes, the convergence dynamics seems to be smoother, highlighting a gap in coordination across countries that might lead to a potential dispersion of efforts.

Furthermore, the club convergence analysis of eco-innovation across EU countries for the period 2012–2021 indicates the formation of three clubs for the overall eco-innovation index, with a clear clustering effect for most EU15 countries at the top of the eco-innovation performance - led by Northern countries - and selected Eastern European countries lagging behind the convergence pattern. When the five dimensions of the general eco-innovation index are disentangled, a further heterogeneity emerges across countries and eco-innovation selected performance features.

By implementing an ordered logit model with results from the club of convergence analysis, we elaborate on the drivers of the clustering process of the eco-innovation dynamics. Our estimations reveal that the economic structure of countries, here represented by the GDP per capita and the degree of economic openness, remains the strongest determinant of a convergence process, in line with the seminal results of Barro and Sala-i-Martin (1992). Quite intriguingly, while GDP per capita has a positive effect on eco-innovation convergence as expected, the degree of openness plays a contrasting role. A possible explanation of this could be rooted in the different structure of the labour market, where innovative capabilities in countries lagging behind in the technological ladder are insufficient to transform the opportunities arising from exposure to external markets into knowledge creation and diffusion.

This last result brings us to formulate two policy implications. First, the implementation of the EU sustainable transition strategy should be complemented by specific policies applied to those markets that are still fragile, such as the labour market and the related knowledge capabilities formation, being at risk of an uneven distribution of benefits and cost from the just transition process. Second, given the positive impulse of cooperative behaviours in knowledge creation across industries and countries, in order to speed up the convergence process and favour countries still lagging behind in the eco-innovative pattern, ongoing investment strategies relying on financial funds such as Horizon Europe or the Next Generation EU should better exploit the opportunities from knowledge co-creative processes, including cross-country coordination as an explicit target.

As is customary, the empirical results achieved in this paper must be considered with some caution. The main limitation of the analysis derives from the data availability of the eco-innovation index only for the period 2012–2021, reducing the possibility to fully exploit the power of the club convergence approach to represent the dynamic pattern of convergence.

As extensions of this research, it would be interesting to extend the study of the determinants to the five dimensions, and to investigate possible connections between this process and the convergence paths in innovation in general or other economic magnitudes. Moreover, given that the extent of diffusion of environmental innovations differs considerably between sectors (Fichter and Clausen, 2021), the in-depth analysis of the five eco-innovation dimensions should be further exploited by comparing results for specific sectors, in order to evaluate the speed of convergence of the EU sustainable transition in different economic areas.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Annex A

Table A1
Ranking of countries, eco-innovation index and dimensions, 2012 and 2021.

	2012						2021					
	Eco-innovation Index	Dim 1 Inputs	Dim 2 Activities	Dim 3 Outputs	Dim 4 Resource efficiency	Dim 5 Socio-economic	Eco-innovation Index	Dim 1 Inputs	Dim 2 Activities	Dim 3 Outputs	Dim 4 Resource efficiency	Dim 5 Socio-economic
Denmark	1	1	12	3	5	5	3	6	12	1	11	4
Finland	2	2	5	1	25	1	2	2	10	2	25	1
Luxembourg	3	3	22	6	1	6	1	5	14	4	1	5
Sweden	4	4	1	2	11	12	5	3	2	3	17	17
Austria	5	9	5	5	12	2	3	11	8	6	15	2
Spain	6	5	3	16	15	14	8	14	3	18	12	14
France	7	7	8	9	7	21	7	8	6	12	8	19
Germany	8	5	21	4	9	16	6	1	15	5	7	16
Portugal	9	16	4	18	23	9	11	16	4	15	22	8
Netherlands	10	14	14	7	4	20	9	7	16	7	5	14
Czechia	11	15	2	22	12	8	13	12	1	20	10	10
Italy	11	11	15	17	3	22	9	13	7	17	1	21
Belgium	13	10	9	8	10	25	15	10	13	9	4	26
Ireland	14	13	10	10	16	26	14	15	5	10	6	24
Romania	14	20	11	23	24	4	23	25	27	24	24	6
Estonia	16	8	27	12	27	3	17	17	23	8	26	3
Latvia	16	18	18	14	8	7	18	20	20	13	14	7
Slovenia	18	12	23	10	20	11	12	4	11	14	19	13
Slovakia	19	22	7	25	6	18	21	22	16	22	9	18
Greece	20	18	18	13	22	12	16	9	22	16	20	11
Croatia	20	24	16	20	14	15	20	21	9	22	16	19
Lithuania	20	17	16	21	18	17	19	18	26	19	13	9
Malta	20	26	13	27	2	24	25	26	19	27	3	25
Cyprus	24	27	25	15	17	10	22	27	25	11	18	12
Hungary	25	23	18	19	18	27	24	19	18	26	23	N/A
Poland	26	21	24	24	21	19	26	23	20	21	20	22
Bulgaria	27	25	26	26	26	23	27	23	24	25	27	23
Rank correlation with index		0.8842	0.5925	0.7355	0.3752	0.4616		0.8702	0.6351	0.8143	0.3399	0.4275

Source: European Commission and own elaboration.

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