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Research article

Contextual drivers of energy demand and supply from renewable sources

Mattia De Rosa [a], Marta Meleddu [b,*], Manuela Pulina [b]

[a] *Dipartimento di Ingegneria Meccanica, Energetica, Gestionale e dei Trasporti (DIME), University of Genova, Italy*
[b] *Dipartimento di Scienze Economiche e Aziendali (DISEA), University of Sassari and CRENoS, Italy*

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ABSTRACT

This study investigates the socio-economic and environmental drivers shaping renewable energy demand and supply within a meso-level setting (Italian regions, 2004–2020). Employing a panel vector error correction mechanism (PVECM) and an integrative biplot analysis, the research outcomes reveal a market equilibrium between demand and supply in the short and long run. Human capital accumulation is identified as pivotal in driving the renewable energy transition. Significant regional heterogeneities indicate challenges in achieving convergence towards sustainability and socio-economic development and well-being. Key empirical implications include enhancing education and vocational training to strengthen human capital and implementing tailored regional strategies for sustainable infrastructure development. These findings support policymakers in formulating targeted policies for a resilient, balanced energy future and addressing regional disparities in renewable energy adoption.

1. Introduction

The recent discourse on climate change highlights the importance of public investment in financing the energy transition, facilitating long-term investment strategies, and expanding the welfare state to boost social protection. The urgency of addressing this trajectory is also driven by its wide-ranging impacts on global ecosystems, economies, and societies [1]. The renewable energy transition is not only a critical component in mitigating greenhouse gas emissions [2], but also in fostering energy security, reducing dependency on fossil fuels, and promoting sustainable economic growth and progress ([3–7]). Indeed, the energy transition stands out as the most significant technological and socio-economic transformation of the past two centuries [8]. Beyond its environmental benefits, it offers the potential for enhanced public health, innovation and job creation ([9,10]).

While the United Nations (UN) 2030 Sustainable Development Goals (SDGs) advocate energy diversification to mitigate emissions, there remains a lack of empirical evidence on the factors influencing renewable energy demand (i.e. consumption) and supply (i.e. generation) ([11–14]). The extant literature predominantly focuses on separate frameworks of renewable energy demand ([15–22]) and supply, although the latter is overlooked ([11,23–26]). This paper aims to contribute to this strand of the literature by focusing on investigating renewable energy demand and supply within a unified, integrated framework. Indeed, within a comprehensive literature review, Gan et al. [27] identified a need for more investigation into the equilibrium between renewable energy supply and demand. This indicates ample opportunity to explore the evolving interaction mechanism between these two facets. For example, Hassan et al.

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[*] Corresponding author.
E-mail addresses: mattia.derosa@unige.it (M. De Rosa), mmeleddu@uniss.it (M. Meleddu), mpulina@uniss.it (M. Pulina).

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[1] provide a global overview of renewable demand and supply, framing several scenarios for the future paths of these segments, although separately. Bilgili et al. [2], within a panel analysis, revealed the role of renewable generation and electricity demand in reducing CO_2 emissions.

Furthermore, while socioeconomic dynamics are recognised as having a significant impact on renewable energy, the literature suggests that these factors still require comprehensive examination ([28–30]), also with a focus on country-specific features [1]. Therefore, enhancing the understanding of socio-economic and environmental behaviours and dynamics is crucial for formulating appropriate policies at both private and public levels to facilitate a successful change.

Departing from the traditional approach of treating renewable energy demand and supply as separate constructs, this paper investigates their contextual drivers within an integrated framework. To this aim, the paper employs data on renewable energy demand and supply, encompassing solar, wind, geothermal, hydropower, biomass and biofuel sources. The research examines both short and long-run impacts by applying a parametric methodology, specifically a panel vector error correction mechanism (PVECM). This methodology is grounded in the neoclassical Solow-Swan and KLEM (capital, labour, energy, materials) models, wherein production is a function of technological progress, physical capital, human capital (i.e. formation and accumulation), natural resources and energy ([2,31,32]).

Anchored in a spectrum of good (e.g. satisfaction with the environment) and bad (e.g. extreme rain, extreme heat, illegal building) SDG indicators, a non-parametric biplot is employed to address potential shortcomings of econometric specifications, such as multicollinearity issues ([33,34]). This approach comprehensively explores the intricate interplay between various socio-economic indicators (i.e., income, human capital formation, and accumulation) and environmental contextual drivers in the energy transition setting, considered a challenge in future research ([2]). For example, institutional quality ([35–37]) and perceived climate change ([38,39]) are relevant indicators to be considered. This study also sheds light on within-country heterogeneity, a facet often overlooked in prior research ([1,40]), yet one that may significantly influence renewable energy demand-supply dynamics in the short and long run.

Building on these foundations and literature gaps, this study assesses the dynamics and interconnections within the renewable energy market. As a first step, it investigates whether a market equilibrium exists between renewable energy demand and supply in the short and long run. Understanding the equilibrium dynamics is crucial for predicting market stability and guiding policy decisions to promote renewable energy use (RQ1). Besides, the study explores the contextual drivers influencing renewable energy demand and supply. Identifying these drivers is essential for comprehending the various factors that impact renewable energy adoption and utilisation, which include socio-economic, geographical, and climatic characteristics (RQ2). The research also examines the dynamic evolution of renewable energy demand and supply over time. Analysing how these components change provides insights into long-run trends and the effectiveness of current energy policies (RQ3). By leveraging macro and regional panel data, Italy serves as a challenging yet illustrative context due to its diverse socio-economic, geographical, and climatic characteristics ([38–43]). Through an integrated multivariate approach (i.e. PVECM and biplot methods), this study contributes to a more informed understanding of dynamics, convergence, and sustainability trajectories within this EU country.

The paper is structured as follows. Section 2 provides an overview of the literature on similar issues. Section 3 describes the relevant setting under investigation. Section 4 presents the parametric and non-parametric methodology. Section 5 highlights the empirical results. Section 6 discusses implications for stakeholders. The final section offers concluding remarks.

2. Literature review

Renewable energy sources are increasingly prevalent and are integral to meeting overall energy demand. This surge in renewable energy usage is contributing positively to both the reduction of CO_2 emissions and economic growth, as assessed by the following literature. For example, Tugcu et al. [16] employed an autoregressive distributed lag (ARDL) approach to cointegration in their study of a group of G-7 countries. Jebli et al. [17] utilised fully modified ordinary least squares (FMOLS), dynamic ordinary least squares (DOLS), and Granger causality testing to assess this trend in Organisation for Economic Co-operation and Development (OECD) countries. Murad et al. [18] conducted an ARDL analysis and a vector autoregressive model (VAR) testing for Granger causality in the Denmark case. Ahmad et al. [19] explored 30 Chinese provinces and cities, while Le Quéré et al. [20] focused on a cluster of eighteen developed countries, employing correlation analyses to support their findings. Similarly, Bilgili et al. [2], for 14 selected EU countries using a PVECM, revealed the effects of renewable electricity supply, the advancement of environment-related technologies, and the dissemination of such technologies on CO_2 emissions reduction.

From a different perspective, the evolving discourse on climate change, coupled with initiatives such as the Green New Deal and considerations of degrowth ([4,44]), underlines the pivotal role of public investment in financing the energy transition. This imperative public action not only facilitates longer investment horizons but also expands the welfare state, thereby augmenting social protection measures. Consequently, it is imperative to conceptualise the energy transition within a more comprehensive framework encompassing various socio-economic and environmental drivers.

Grounded on Chang et al. [45], Sadorsky [46] and Marques et al. [15], scholars have extensively examined various determinants of renewable energy demand, complementing traditional economic variables like income and prices ([47,48]). Apergis and Eleftheriou [49], employing a PVECM, encompassed institutional and political factors. Their study revealed a statistically significant influence of these institutional variables on renewable energy demand across Europe, Asia, and Latin America. Employing an augmented mean group approach for G-7 countries, Huihui et al. [50] confirmed the positive impact of democracy and institutional quality on the renewable energy transition. Granger causality tests conducted by Apergis and Eleftheriou [49] revealed that, when considered alongside other controls, the average number of years of education for individuals aged 15 and above positively correlated with long-run outcomes. Furthermore, the authors unveiled a short run unidirectional connection between the formation of human capital and renewable energy adoption, except for Latin America.

Furthermore, Yao et al. [28] identified the human capital index as a significant determinant of renewable energy demand across a panel of OECD countries, accounting for structural breaks. Their study highlighted how human capital formation facilitates greater adoption of clean energy, generating positive social and environmental externalities. Human capital also plays a crucial role in driving innovation and supporting research and development (R&D), thereby accelerating the transition from resource-intensive to capital-intensive human activities. This is particularly evident in sectors requiring high-skilled abilities, such as R&D in energy technology ([51]). Furthermore, Hao and Shao [26], employing a two-way fixed effect model for a panel of 118 countries from 1995 to 2015, discovered that countries experiencing climate change and relying less on carbon-intensive processes tend to allocate higher quotas for renewable energy supply.

From a macroeconomic perspective, the literature has explored the intricate relationship between human capital and energy demand. Salim et al. [52] for China and Alvarado et al. [12] for a group of OECD countries, concluded that no significant relationship exists between human capital and overall energy demand. Conversely, the authors found that human capital accumulation and knowledge dissemination contribute to a decrease in traditional energy demand and promote energy conservation. In contrast, studies examining the impact of human capital on renewable energy demand have yielded mixed results ([21,22,29]). Wang et al. [30], employing a double fixed effect model for 30 Chinese provinces, demonstrated the pivotal role played by human capital in driving energy consumption.

From a microeconomic perspective, empirical evidence suggests that individuals with higher levels of education tend to be more environmentally conscious and consume less energy ([53,54]). Furthermore, Polcyn et al. [48] conducted a bibliometric analysis focusing on selected EU countries, revealing that renewable energy demand is influenced not only by traditional socio-economic indicators such as investment, trade and human capital but also by various other relevant drivers. These include environmental degradation, urbanisation, institutional quality, and climate change concerns. Illegal housing is often driven by inefficient local institutions or organised criminal groups ([36,50,55–57]). These land abuses, compounded by the unpredictability and intensification of extreme weather events, present significant challenges for local communities ([35,38,39]). The literature suggests that policymakers need to foster a balanced development approach that harmonises human activities with the preservation of landscapes and ecosystems, especially in vulnerable areas like potential flood zones and lowlands ([36,37,56]).

Local communities and consumers can address further carbon neutrality initiatives and ecological footprint considerations. Wall et al. [58], utilising a structural equation model in their study of Thailand, revealed that consumers' willingness to adopt renewable energy is primarily driven by environmental concern and trust in its beneficial impact. Interestingly, cost did not emerge as a statistically significant factor influencing adoption. Similarly, Ali et al. [59], focusing on the Shandong province in China, found strong consumer support for renewable energy, largely attributed to its environmental benefits. Their research highlighted that younger, more educated individuals with higher incomes were remarkably willing to pay for green energy, underscoring the importance of public awareness campaigns and emphasising the broader societal benefits of renewable energy adoption. These aspects are particularly relevant for the development of local energy communities ([60]), which consist of local legal entities controlled by individuals, local authorities, and small/medium companies created to manage and exchange energy generated in the community boundary (either physical or virtual) with the final goal of providing social, environmental and economic benefits to the participants ([3]). To achieve this goal, effective social engagement strategies involving all community stakeholders and transparent policies to increase the

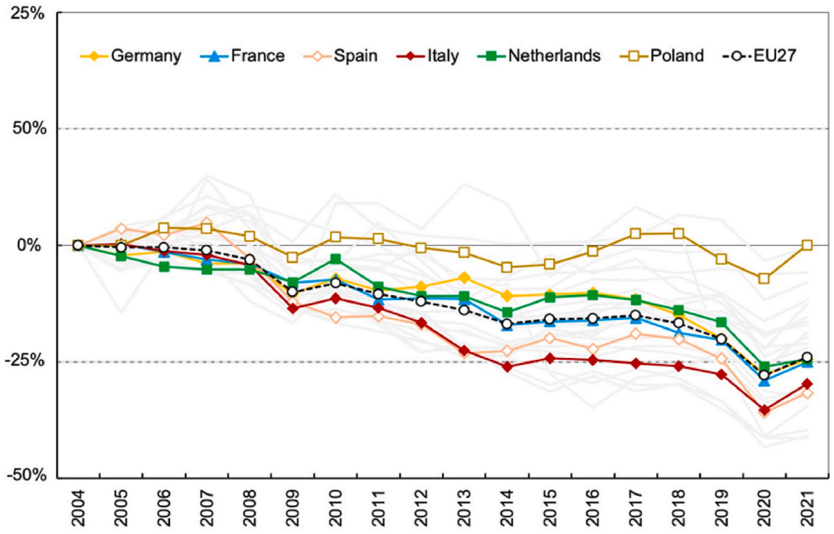

Fig. 1. Percentage variation of greenhouse gas emissions in the EU-27 (2004–2021; 2004 baseline). Elaboration on EUROSTAT data (Eurostat, 2020).

renewable energy supply should be implemented ([5,7]). Furthermore, as emphasised by Hassan et al. [1], country-specific features still need to be analysed. For example, through structural equation modelling, Ali et al. [59] explored the relationship between public behaviour and the energy transition in three Italian macro-regions. Despite growing awareness, Italian consumers still prioritise traditional factors over sustainability, and regional disparities persist.

Empirical evidence concerning the determinants of renewable energy supply remains limited. Building on the seminal work of Marques et al. [15], a few studies have explored determinants influencing renewable energy supply across groups of countries, using varying sample sizes, the extensive study by Marques et al. [24] covering 46 countries. Some studies, such as those by Liu et al. [25] and Marques et al. [24], have focused on the impact of policy instruments on installed capacity and generated renewable energy, while others, such as Lin and Omoju [61], have explored competitiveness issues within the energy market. Przychodzen and Przychodzen [11] investigated specific economic determinants, including growth, unemployment, government debt, and the Kyoto Protocol.

3. The policy setting and the case study

The EU has shown unwavering commitment to setting ambitious targets to promote the integration of renewable energies into the power system. A key responsibility is to facilitate member states' coordination towards enhancing the sustainability and security of the energy supply ([62]) while promoting the harmonisation of proposals and protocols ([63]).

The combination of the EU policies supporting energy efficiency measures ([64]) and renewable energy systems (European Directive 2009/28/EC) led to a reduction in greenhouse emissions in the EU-27 of about 25 per cent compared to the 2004 baseline. Figure 1 shows the variation in greenhouse gas emissions in the EU, highlighting the six major contributors (Germany, France, Italy, the Netherlands, Poland, and Spain, which represent approximately 70 per cent of total emissions in the EU) and the EU-27 average. All countries except Poland achieved significant greenhouse emissions reductions. Italy gained a notable decline in greenhouse gas emissions due to implementing energy efficiency measures backed by public incentives and the growing utilisation of renewable energy.

Renewable energy is critical in achieving decarbonisation targets by offering sustainable alternatives to fossil fuels, significantly reducing greenhouse gas emissions and addressing climate change. The European Directive 2009/28/EC set an initial target of 20 per cent renewable energy demand by 2020 for the entire EU; in 2018, this was revised to a more ambitious goal of 32 per cent renewable energy demand by 2030 (European Directive 2018/2001/EU). Despite these targets, as of 2019, the EU-27's share of renewable energies in total energy demand was only 19.7 per cent, falling short of the policy target set in 2009 ([65]). Figure 2 illustrates the share of total energy supply for renewable resources in Italy, compared to the EU-27, between 2004 and 2021.

Italy experienced a convergence trend towards the EU-27 profile over 2004–2017, while lower values were observed in the most recent years (2018–2021). Although Italy is better positioned than many other European countries (e.g. France and Germany), its renewable energy demand is far lower than that of countries such as Sweden (56.4 %), Austria (33.6 %), and Portugal (30.6 %), as reported in Eurostat [65].

Figure 3 shows the share of electricity supply from renewable (solar, wind, geothermal, hydro and biomass) versus non-renewable sources (coal, oil, and natural gas) in Italy from 2004 to 2021. Despite a reduction trend, non-renewable fossil fuels still accounted for more than 60 per cent of the total primary energy used to generate electricity in Italy in 2021, with a predominant penetration of natural gas (85 per cent of the total electricity from non-renewable sources in 2021), compared to coal (10 per cent in 2021) and oil (5 per cent in 2021). The penetration of renewables in the national electric network increased from 20 per cent in 2004 to about 40 per cent in 2021, with a peak of 42 per cent in 2014. Although an overall inverted trend occurred for the two series at the macro level, the convergence has tended to be volatile within the 35–41 per cent range since 2013. These values indicate possible critical issues

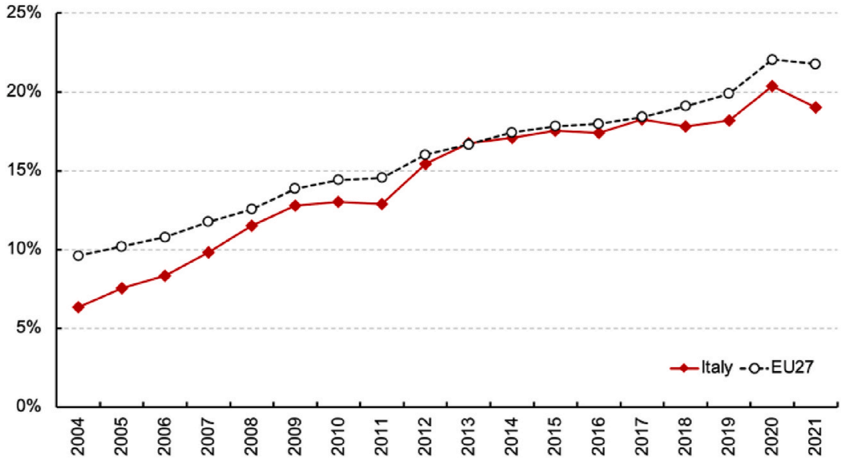

Fig. 2. Share of total energy supply from renewable sources in Italy and EU-27 average (2004–2021). Elaboration on EUROSTAT data (Eurostat, 2020).

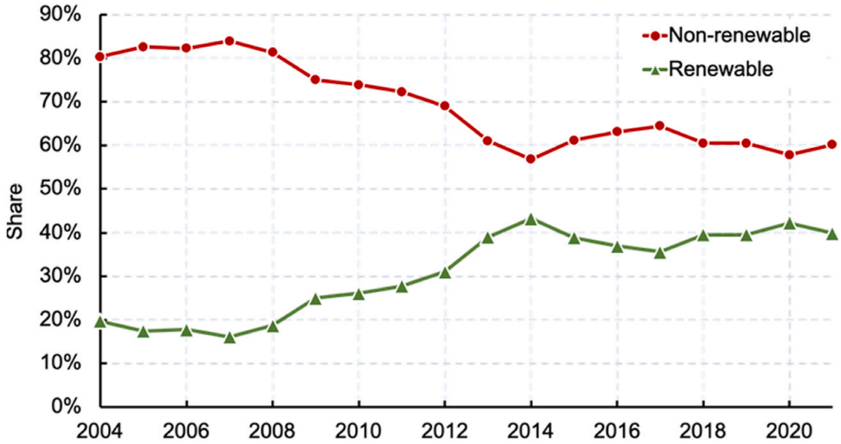

Fig. 3. Share of electricity supply from renewable and non-renewable in Italy (2004–2021). Own elaboration on EUROSTAT data (Eurostat, 202.

regarding renewable energy continuity and capacity that cannot deliver a complete substitution of traditional technology ([66]). Generally, one of the main issues in achieving high shares of electricity supply from renewables is related to the intrinsic stochasticity of their production. Since the national grid requires a continuous balance between demand and supply to operate, high penetration of electric supply systems with intermittent/aleatory production, such as solar and wind systems, can stress the national grid regulation, thus leading to its reduced resilience and reliability ([67]).

In 2011, Legislative Decree 28/2011 integrated the EU target. One year later, Legislative Decree 15/2012 (the so-called burden-sharing decree) entrusted regions and autonomous provinces with their objectives ([68]). Before these legislative measures, the Italian government ordered regions to adopt a regional energy plan (REP), fulfilled by each region in different years between 2003 and 2010 ([69]). The aims were to contribute to CO2 reduction, decrease energy expenditure, and stimulate employment and innovation in the renewable sector.

Table 1 presents the REP adoption of each Italian region and the differences between the middle-term achievements and the burden-sharing targets in 2012, 2014, 2016, and 2018 (except for the transport sector). Overall, the share of gross final energy demand covered by renewable sources exceeded the forecast; the only exceptions were Liguria, Lazio, and Sicilia, especially in the remaining years under analysis.

Notably, in 2020, the Italian Integrated National Energy and Climate Plan ([70]) established a new target of 30 per cent for renewable energy demand to be achieved by 2030. Moreover, the NECP set the renewable energy supply objective at approximately 55 per cent in 2030 (34.1 per cent in 2017), with photovoltaic power surpassing the primary current source, hydropower. These objectives can be achieved by implementing the necessary infrastructures and monitoring related social impacts. Figure 4 highlights the pattern of renewable energy supply and demand in the Italian regions.

Table 1
Regional energy plan (REP), renewable energy demand and burden-sharing target.

Regions	REP	Differences between intermediate achievement and burden-sharing target				Final target
		2012	2014	2016	2018	2020
Valle d'Aosta	2003	1.7 %	23.6 %	37.1 %	32.%	52 %
Liguria	2003	1.6 %	−0.6 %	−2.1 %	−3.6 %	14 %
Piemonte	2004	4.9 %	6.4 %	5.9 %	4.4 %	15 %
Umbria	2004	11.%	11.5 %	12.8 %	11.8 %	14 %
Veneto	2005	9.4 %	1.4 %	1.1 %	8.2 %	10 %
Marche	2005	9.2 %	8.4 %	6.9 %	5.4 %	15 %
Calabria	2005	18.3 %	2.9 %	19.2 %	17.7 %	27 %
Molise	2006	14.9 %	13.0 %	12.7 %	9.4 %	35 %
Sardegna	2006	14.3 %	14.6 %	11.7 %	8.8 %	18 %
Friuli V.G.	2007	9.1 %	1.4 %	1.0 %	8.6 %	13 %
Emilia R.	2007	4.6 %	5.6 %	4.6 %	3.5 %	9 %
Puglia	2007	5.5 %	6.3 %	5.5 %	4.6 %	14 %
Lombardia	2008	4.2 %	5.4 %	5.0 %	3.8 %	11 %
Toscana	2008	4.8 %	5.0 %	4.7 %	2.9 %	17 %
Lazio	2008	1.8 %	1.5 %	0.0 %	−1.3 %	12 %
Abruzzo	2009	12.4 %	12.8 %	11.3 %	1.5 %	19 %
Campania	2009	7.0 %	5.7 %	4.5 %	2.2 %	17 %
Sicilia	2009	2.6 %	2.8 %	0.8 %	−0.6 %	16 %
Basilicata	2010	15.2 %	15.4 %	16.2 %	2.0 %	33 %
Trentino	1997–2010*	17.6 %	18.9 %	21.5 %	18.9 %	36 %

In almost all the Italian regions, renewable energy supply and demand slightly increased over the period. Valle d'Aosta, which adopted the REP in 2003, and, as first-mover regions, Trentino—as an average between the autonomous provinces of Bozen (REP = 1997) and Trento (REP = 2010)—show the highest levels of renewable demand and supply. Renewable energy demand and supply trends in Italy are also influenced by EU policies (European Directive 2018/2001/EU) aimed at increasing renewable energy use. However, variations in these trends are mainly due to Italy's unique economic and industrial conditions, energy infrastructure and funding availability. Moreover, the administrative structure, with both local and regional governments sharing responsibility for energy-related issues has an impact.

4. Methodology

4.1. The parametric framework

The first step of the analysis assesses the (un)balance between renewable energy supply (*REg*) and demand (*REc*) in the short run and the long run (RQ1; [15,71]). Equation (1) expresses the baseline univariate framework:

$$RE_{Cit} = f\ (RE_{Git}) \tag{1}$$

A panel analysis provides valuable insights, focusing on the dynamics within a specific region (*i*) during the time frame (*t*). In matrix notation, the PVECM of order one, as an exemplification, can be written as in equation (2):

$$\Delta RE_{i,t} = c_i + \Gamma_1\ \Delta RE_{i,t-1} + \Pi\ RE_{i,t-1} + \epsilon_{it} \tag{2}$$

where Δ is the first difference operator; c_i is the 2×1 vector of constant specific to each region *i*, controlling for heterogeneity through fixed effects; Γ_1 is the matrix of coefficients of the lagged dependent variables that elicit short-run information; and Π is the 2×2 matrix of long-run cointegrating relationships. If the null hypothesis of no cointegration is rejected, one would expect rank (Π) < K (i.e. a rank lower than the number of the variables) and so one linear equation that detects long-run information (*ECM*). From an economic perspective, a negative coefficient of the first lag of the error correction mechanism (ECM) indicates that disequilibrium leads to corrective actions that bring the system back into balance. For example, if renewable energy demand exceeds supply in the short run,

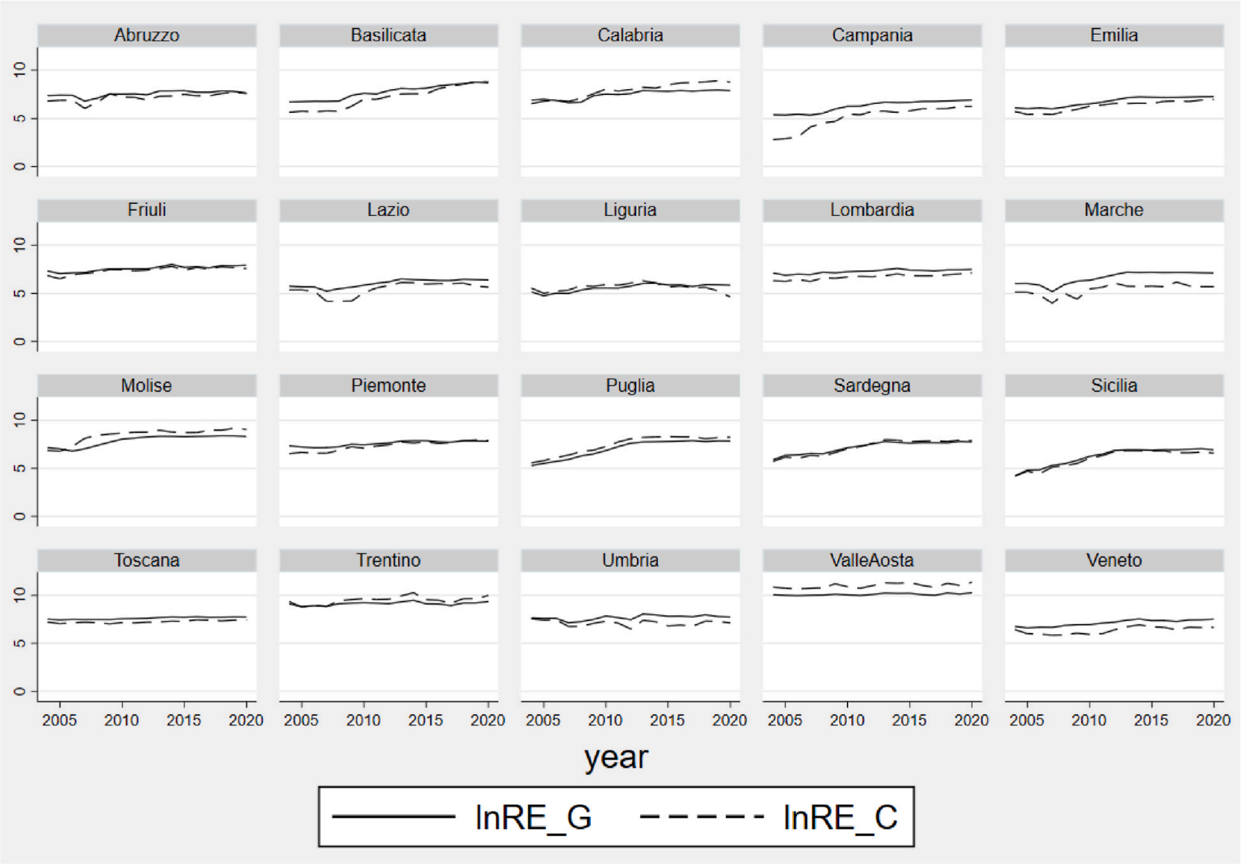

Fig. 4. (Log) renewable energy supply (lnRE_G) and demand (lnRE:C) (2004–2020, Italian regions). Elaboration on TERNA data.

prices may rise, leading to increased supply and decreased demand until equilibrium is restored. This matrix comprises the adjustment coefficients (α) representing the speed towards the long-run equilibrium. The long-run coefficients (β) show how each variable contributes to the long-run equilibrium; if a log-log model is estimated, the coefficients are elasticities. ε the 2×1 residual vector is assumed to be white and normally distributed ([72]). Within this endogenous framework, *RE* defines renewable energy demand (RE_C) and renewable energy supply (RE_G) respectively ([24,49,73,74]).

This PVECM assesses whether renewable energy demand influences renewable energy supply, vice versa, or if the two indicators are simultaneously determined. It is reasonable to assume that, in the real world, changes in demand can influence supply decisions, and vice versa. Hence, assessing the simultaneity of demand and supply dynamics and short and long-run behaviour can help understand how changes in one variable affect the other and how markets adjust over time. To this end, the PVECM and the temporal Granger causality test provide a first insight into this relationship, despite the lack of price data, given the highly volatile conditions for a competitive market at a regional level. By examining simultaneity, impacts, the ordering relationship of these two indicators, and their predictive power over each other, short-run and long-run linkages mirror a market equilibrium (RQ1). Within the Granger causality framework, the temporal relationship, if any, can be unidirectional (i.e. demand-led or supply-led as alternative hypotheses), or bidirectional (i.e. demand and supply drive each other). These tests are run in the short run—that is, on the variables expressed in the first difference to elicit dynamics, hence testing the joint statistical significance of their lags—and in the long run, through the cointegration mechanism that detects convergence ([72,75]).

As an expansion of the univariate framework, the relevant theoretical framework builds on the standard new neo-classical Solow-Swan and KLEM models that endogenously elicit the drivers of economic growth and account for the Solow residual ([31,76–79]). The specification presented in this paper moves from these economic developments, incorporating demand and supply of renewable energy as further indicators to explore possible market equilibrium and short and long-run dynamics. Within a multivariate framework, the per capita economic growth depends on technological progress, physical and human capital formation and accumulation, and energy, as in equation (3):

$$Y_{it} = f\left(RE_{it}, HC_{it}\right) \tag{3}$$

where *Y* is the disposable income per capita, RE is renewable energy (demand and supply, respectively), and HC is the human capital component that assesses the contribution of education formation, accumulation, and labour to the economy. Assuming endogeneity, the associated generic equation is as follows in equation (4):

$$\Delta Y_{\ i,t} = c_i + \Gamma_1\ \Delta X_{i,t-1} + \Pi\, X_{i,t-1} + \varepsilon_{it} \tag{4}$$

where $c_{i,}$ Γ and Π are the parameters to be estimated and ε is the residual vector, which is assumed to be white and normally distributed; Δ is the first difference; *X* defines renewable energy demand or renewable energy supply, respectively, income, and human capital (i.e. formation and accumulation). Hence, as a further robustness check, it provides empirical evidence of a (un)balance between renewable energy demand and supply (RQ1). Furthermore, it unveils the interconnections between traditional economic indicators and renewable energy, as well as the dynamics in the short and long run (RQ2; [80–82]). All the indicators are defined in a natural logarithm for an immediate interpretation of the coefficients in elasticities and elicit non-linearities.

4.2. The non-parametric approach

A multivariate framework based on a biplot is adopted to expand knowledge on the dynamic evolution, convergence, and interconnections of renewable energy further ([83]). The theoretical expression is as follows in equation (5):

$$\mathrm{Y} \approx (\mathrm{N}_2\ \Phi_2^{\alpha})\ (\mathrm{K}_2\ \Phi_2^{1-\alpha})' \tag{5}$$

where *Y* represents the data of interest; $(N_2\ \Phi_2^{\alpha})$ includes the plotting coordinates corresponding to rows; and $(K_2\ \Phi_2^{1-\alpha})$ contains the plotting coordinates corresponding to columns. A biplot decomposes the data matrix into a portion associated with a clustering of *N* decision-making units, marked by points, and a portion associated with *K* indicators marked by arrows. Alpha (α) is normalised between zero and one ([83]). This non-parametric approach is hardly employed in the literature on energy issues ([33,34]). The biplot is a graphical tool for effectively visualising cross-sectional and multivariate data. It holds several advantages. It does not depend on predefined assumptions regarding the data distribution. As in the present study, data can be easily standardised to have a mean of zero and a standard deviation of one for a homogeneous scale and comparison. The biplot captures inherent relationships and patterns and represents complex data in a more manageable format.

Compared to parametric approaches, the biplot accommodates highly correlated indicators, simultaneously displaying indicators and observations in a low-dimensional space. Based on these technical features, this integrative framework includes various socio-economic and environmental objective and subjective indicators (RQ3) that can capture regional heterogeneity and further dynamics.

5. Empirical results

5.1. Parametric results

The parametric framework is operational by employing Italian regional data from 2004 to 2020. The matrix is constructed on data retrieved from the Italian Institute of Statistics. *Y* is the disposable income per capita, which, in equilibrium, also proxies the gross domestic product (GDP). This economic indicator, collected from the Italian National Institute of Statistics (ISTAT, [104]), accounts for SDG 10, namely the goal of reducing inequality within and amongst countries. *RE* is renewable energy (demand and supply) that incorporates physical capital (i.e. infrastructures) and natural resources as raw materials. Specifically, this indicator relates to domestic renewable energy that includes solar, wind, geothermal, hydropower and bioenergy, and the public and private sectors. It mirrors SDG 7, namely the goal to ensure access to affordable, reliable, sustainable and modern energy for all. The human capital component is disentangled in the following indicators: human capital formation (*HCF*) as the share of 25–64-year-olds who hold a high school degree; and human capital accumulation (*HCA*) as the share of overeducated employees with a university education. The latter also captures labour as a factor of production. Data are retrieved from ISTAT and mirror SDG 4, which is quality of education. Tables 1.A, 2.A and 3.A in the Appendix provide full details on definitions, data sources, descriptive statistics and correlations.

5.1.1. *Panel unit roots and panel cointegration*

As a first step, the integration order of the economic indicators is established. Table 2 reports the outcomes for a set of panel unit root tests. The LLC ([84]; which does not require the residuals to be homoscedastic across panels), Breitung [85], HT ([86]), and H-HC tests ([87]; heteroskedasticity) assume that the autoregressive parameters are common across cross sections. Only in the H-HC test was the null hypothesis assumed to be stationary. The IPS ([88]), ADF-F, and PP tests ([89,90]) allow for individual unit root processes so that the autoregressive coefficients may vary across cross-sections.

The Akaike information criterion indicates the appropriate number of lags to control for serial correlation. On balance, the non-stationarity hypothesis holds, and the variables of this study may be integrated, of order one (Table 2).

The next step of the investigation is to test for a common long-run equilibrium and further prove the integration status of the variables. Following the Pedroni test ([91,92]), two main cases were reported. For the within-dimension approach, four statistical variables were reported, namely the modified variance ratio (MVR), modified Phillips-Perron (MPP), non-parametric panel PP, and the parametric panel augmented Dickey-Fuller (ADF). These statistical variables assume the homogeneous hypothesis that the autoregressive coefficients are pooled across the set of regions for the unit root tests on the estimated residuals, considering the common time factors and heterogeneity across regions. Based on the between-dimension approach, three statistical variables were reported: MPP, PP, and Dickey-Fuller (ADF). These statistics assume the heterogeneous hypothesis; that is, they are based on the averages of the individual autoregressive coefficients associated with the unit root tests of the residuals for each region. All tests denote an asymptotic standard normal distribution. The heterogeneous intercept (c), intercept set to zero (no c), and demean were reported in all these tests. The latter specification reduces the impact of cross-sectional dependence by subtracting the cross-sectional averages from the series ([84]). The Kao test ([93]) and five complementary tests were used. Unlike the Pedroni test, they specify cross-section specific intercepts (*c*) and the demean. The Westerlund test ([94]) reports the variance ratio (VR) and tests whether the variables are cointegrated in some panels. In most tests, the null hypothesis of no cointegration is rejected at least at the 5 per cent level, confirming the existence of a long-run relationship and, hence, the integration status of order one (Table 3).

5.1.2. *Univariate framework*

A univariate framework involves an assumed market equilibrium between renewable energy demand and supply (see Equation (2)). Table 4 reports the long-run coefficients within the PVECM (1,1) specification.

There is a positive and simultaneous relationship between demand and supply, although supply exerts a relatively higher impact on demand. Table 5 reports short-run dynamics, the error correction term, and the temporal Granger causality outcome.

The coefficients of the first difference of the dependent variable at time t_0 (*DRE_C* and *DRE_G*, respectively) are the impact coefficients in the short run. Notably, these coefficients are strongly statistically significant, implying simultaneity within a joint equilibrium. However, the magnitude of the short-run coefficients shows that the impact of supply on demand is higher than the reverse.

As a further outcome, the first lag of the ECM shows a negative and statistically significant coefficient, implying a convergence towards a common equilibrium. Moreover, the speed of the adjustment is also faster in the demand equation ($\alpha = -0.362$), which implies that renewable energy demand responds more rapidly to previous deviations from the long-run equilibrium. Notably, a

Table 2
Panel unit root analysis (log, 2004–2020).

Variables	LLC	IPS	HT	H-HC	Breitung	ADF-F	PP-F
RE_C	**−3.809 (0.0001)**	−1.162 (0.1227)	0.854 (0.7054)	**34.277 (0.000)**	2.812 (0.9975)	**131.429 (0.0000)**	**90.737 (0.0000)**
RE_G	**−8.100 (0.0000)**	**−2.262 (0.0119)**	0.883 (0.9025)	**37.233 (0.000)**	2.895 (0.9981)	**113.283 (0.0000)**	**94.809 (0.0000)**
Y	**−1.625 (0.0520)**	0.298 (0.6171)	0.789 (0.1218)	**26.257 (0.000)**	3.014 (0.9987)	21.181 (0.9937)	30.928 (0.8478)
HCF	3.274 (0.9995)	10.918 (1.000)	3.295 (1.0000)	**8.520 (0.000)**	3.740 (0.9999)	11.308 (1.0000)	52.122 (0.0949)
HCA	1.754 (0.9603)	9.680 (1.0000)	1.956 (1.0000)	**12.434 (0.000)**	4.046 (1.0000)	16.521 (0.9996)	29.370 (0.8920)

Notes: Only with constant; p-values in parentheses. For H-HC (Hadri, heteroscedasticity), the null hypothesis = no unit root; in bold, the unit root assumption holds at least a 10 % significance level; probability is in parenthesis.

Table 3
Panel cointegration (results with HCF).

	PEDRONI		
	No constant	Constant	Demean
Within (panel)			
Modified variance ratio	**−2.3402 (0.0096)*****	**−2.8259 (0.0024)*****	**−3.2989 (0.0005)*****
Modified Phillips-Perron (MPP) t	0.5992 (0.2745)	1.0841 (0.1392)	1.2605 (0.1037)
PP t	**−3.0435 (0.0012)*****	**−3.5660 (0.0002)*****	**−1.9869 (0.0235)****
Augmented Dickey-Fuller (ADF)	**−2.7894 (0.0026)*****	**−3.7950 (0.0001)*****	**−3.1406 (0.0008)*****
Between (group)			
MPP t	**2.0910 (0.0183)****	**2.6724 (0.0038) *****	**2.5276 (0.0057)*****
PP t	**−4.2202 (0.0000)*****	**−4.4841 (0.0000)*****	**−3.4811 (0.0002)*****
ADF	**−3.8075 (0.0001)*****	**−4.7443 (0.0000)*****	**−4.4701 (0.0000)*****
	KAO		
	Constant		***Demean***
Modified Dickey-Fuller (MDF) t	**−3.5022 (0.0002)*****	–	**−2.0779 (0.0189)****
DF t	**−3.4316 (0.0003)*****	–	**−2.7895 (0.0026)*****
ADF t	**−2.9543 (0.0016)*****	–	**−2.4127 (0.0079)*****
UMDF t	**−3.3207 (0.0004)*****	–	**−3.1935 (0.0007)*****
UDF t	**−3.3601 (0.0004)*****	–	**−3.3210 (0.0004)*****
	WESTERLUND		
	Constant	***All panel***	***Demean***
Variance ratio	−0.8348 (0.2019)	−0.8223 (0.2054)	−0.0092 (0.4963)

Notes: c (constant); in bold, statistical significance at 5 % (**) and 1 % (***); p-values in parenthesis; null hypothesis: no cointegration; the results are equivalent for *HCA* as a covariate.

Table 4
Long run coefficients, PVECM (1,1).

Dependent	DRE_C	DRE_G
DRE_C	–	**1.011*****
DRE_G	**0.947 *****	-

Notes: Robust standard errors correcting for heteroscedasticity and autocorrelation; *** significance at 1 %.

Table 5
Short run dynamics, ECM and temporal Granger causality, PVECM (1,1).

Dependent	DRE_C	DRE_G	ECM
DRE_C	–	**1.204***** (0.23)	**−0.362*** (10.01***)**
DRE_G	**0.500***** (0.23)	-	**−0.1783** (6.73**)**

Notes: Robust standard errors; impact coefficient at time t_0; joint F-statistic on the first lag in parenthesis (H0: no Granger causality); statistical significance at 10 %(*), 5 %(**), 1 % (***).

bidirectional temporal Granger causality runs from renewable energy demand to supply, and vice versa, but only in the long run. In fact, the null hypothesis of no Granger causality is rejected in both equations (joint F-test in parenthesis). Overall, there is empirical evidence of a simultaneous equilibrium between demand and supply.

5.1.3. *Multivariate framework: long-run dynamics*

The next step is to run a multivariate framework (see Equation (2)). The estimation results for renewable energy demand and supply are presented in Tables 6 and 7, alternatively for HC formation (*HCF*) and accumulation (*HCA*), as a further robustness check. Notably, these two human capital indicators are highly correlated (see Table 3.A).

The findings within the renewable energy demand-supply framework reveal several noteworthy dynamics in the long run. As

Table 6
Long-run renewable energy demand (RE_C) estimation.

Models	RE_G	Y	HCF	HCA
LR coefficients (N=320)	**1.362*****	**0.525****	**−0.538*****	/
LR coefficients (N=320)	**0.608*****	**3.151*****	/	**1.077*****

Notes: Long run (LR) coefficients; ***p < 0.01, **p < 0.05, *p < 0.10.

anticipated, energy supply exerts a positive impact on demand; conversely, energy demand positively impacts energy supply. This outcome confirms the results obtained in the univariate framework.

In examining the demand equation, the coefficient of income consistently displays a statistically significant coefficient, implying that a higher level of wealth leads to higher consumption of renewable energy ([40]). However, in the energy supply equation, the income coefficient consistently displays a negative sign and is statistically significant when considering human capital formation within the specification. This outcome suggests potential substitution effects among competitive sectors driven by non-renewable traditional sources.

Exploring the impact of human capital, findings between the demand and supply equation diverge. Only human capital accumulation exerts a highly significant and positive impact on renewable energy consumption. This outcome further confirms that more educated people are more aware of the environment and consume more renewable energy ([59]). Furthermore, human capital formation and accumulation exhibit positive and statistically significant effects on supply.

As a further robustness check, Table 3.B and Table 4.B (Appendix B) report long-run elasticities obtained running demand and supply as separate frameworks. After controlling for potential multicollinearity, the estimation further supports remarkable substitution effects with traditional energy sources on the supply side. Consistently, human capital accumulation emerges as a significant driver of the renewable energy transition, reinforcing its importance in shaping the energy landscape of the future transition (RQ2).

5.1.4. *Multivariate framework: short-run dynamics*

As a further outcome, the short-run dynamics are assessed within a dynamic PVECM (1,1), within a multivariate framework (Table 8).

In the short run, a simultaneous relationship holds, as revealed by the statistical significance of the coefficients of the first difference at time t_0. The impact of the growth of supply on the growth of demand (Model $1 = 1.40$; Model $2 = 1.28$) is also higher than the reverse (Model $1 = 0.45$; Model $2 = 0.43$), confirming the findings in the univariate framework (see Table 5). However, there is no support for a temporal relationship, as the joint F-test on the first lag confirms the null hypothesis (i.e. no Granger causality).

Moreover, the coefficient of the first lag of the ECM is consistently significant at the 1 per cent level, exhibiting the anticipated negative sign in both the demand and supply equations. Consistently, a bidirectional Granger causality is supported in the long run. These findings further confirm a convergence towards the long-run equilibrium, corroborating results obtained in the univariate framework and serving as a robustness check (RQ1).

Furthermore, in the short run, a consistently negative impact is exerted on the renewable energy supply by economic growth (*DY*) and human capital formation growth (*DHCF*) (see Model 1 and Model 2). This outcome is consistent with substitution effects; hence, traditional energy sources still play an important role in the Italian economy. However, the growth of human capital accumulation (*DHCA*) positively impacts renewable energy supply, although weakly. This outcome highlights the role of human capital development and training in boosting renewable energy sources from the supply side (RQ2). As a confirmation of the long-run outcome, economic growth (*DY*) exerts a positive effect on energy consumption growth (*DLRE_C*), although only in Model 2 is the coefficient statistically significant at 1 per cent.

These results shed light on the intricate interplay between energy demand, supply dynamics, and the influence of socioeconomic indicators, offering valuable insights for policymakers and stakeholders steering the transition towards renewable energy sources.

5.2. *Non-parametric results*

The parametric empirical framework is further expanded by introducing good and bad indicators (see Tables 1.A and 2.A in the Appendix for full details). Specifically, as a good indicator, satisfaction with the environment (*ENSA*) accounts for SDG 11, namely sustainable cities and communities. *ENSA* is a subjective indicator defined as the percentage of those satisfied with the environment (source: ISTAT). As a bad indicator, perception of climate change (*PCC*) mirrors SDG 13, which is the call to take urgent action to combat climate change and its impacts. *PCC* is a subjective indicator and is defined as the percentage of those who are concerned about climate change. Within SDG 13, as exogenous and objective controls, extreme rain (*EXR*) and extreme heat (*EXH)* account for the number of days with extreme weather conditions. As a further mediator for using the land, illegal building (*IB*) accounts for illegal new housing (source: ISTAT). This bad indicator reflects SDG 11, sustainable cities and communities. Illegal houses are normally detached, built by the middle class, on agricultural land or in coastal and mountain settings, and driven by inefficient local institutions, or even organised criminal groups ([50,55,57]). This type of building also tends to be in isolated and fragile landscapes, by the riverside and in the countryside ([56]).

A visual biplot provides an intuitive representation based on a scatterplot with three distinctive elements. Arrows symbolise the indicators and their main statistical features. The arrow's length reflects the indicator's contribution to the overall variation in the data, with longer arrows representing indicators with higher contributions to the variability. The direction of the arrow reflects the

Table 7

Long-run renewable energy supply (RE_G) estimation.

Models	RE_C	Y	HCF	HCA
LR coefficients (N=320)	**0.700*****	**−1.164*****	**1.126*****	/
LR coefficients (N=320)	**0.615*****	−0.476	/	**0.520*****

Notes: LR coefficients and ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

Table 8
Short-run dynamics and panel Granger causality PVECM (1,1) (2004–2020).

		Explanatory variables					
		DRE_C	DRE_G	DY	DHCF	DHCA	ECM
		Short run					Long run
Model 1 Dependent variables	DRE_C	–	**1.400***** (0.00)	0.769 (1.70)	−1.635 (2.01)	/	**−0.346**** **(8.29***)**
	DRE_G	**0.454***** (0.00)	–	**−1.323***** **(4.97**)**	**−1.410***** **(3.44*)**	/	**−0.279***** **(16.69***)**
	DY	0.003 **(9.32***)**	**−0.031***** **(29.92***)**	–	−0.041 (0.15)	/	**−0.206***** **(24.11***)**
	DHCF	**−0.014***** (0.00)	**0.029**** (0.14)	0.007 (0.32)	–	/	**−0.103***** **(28.39***)**
Model 2 Dependent variables	DRE_C	–	**1.283***** (0.22)	**1.331**** (0.76)	/	−0.117 **(4.42**)**	**−0.278**** **(7.51**)**
	DRE_G	**0.430***** (0.04)	–	**−1.306***** **(6.29**)**	/	**0.218*** (0.94)	**−0.310***** **(23.03***)**
	DY	0.007 **(4.78**)**	**−0.040***** **(31.72***)**	–	/	−0.026 **(14.90**)**	0.001 (2.91)
	DHCA	−0.006 (0.12)	**0.025**** (0.39)	0.026 (0.02)	/	–	**−0.196***** **(38.59***)**

Notes: D = first difference; PVECM (1,1) = one lag dynamic specification; short-run impact coefficients (at time t); in parenthesis, joint F statistic on the first lag (H0: no Granger causality); in bold, statistical significance at * (10 %), ** (5 %) and *** (1 %); robust standard errors; in bold and italics, a positive bidirectional impact for renewable energy demand and supply.

relationship and covariance structure with other indicators. High correlation, or similarity, is represented by similar directions and nearly parallel arrows. (Nearly) perpendicular arrows represent orthogonality. A negative correlation is represented by arrows pointing in opposite directions. Each point represents the observation or decision-making unit. The proximity of points to a particular arrow denotes similarities, indicating a strong association. Points that deviate from the arrows suggest unique values or patterns that may be outliers or distinct observations in the dataset. Dimensions (or factors) in the biplot, as extracted through a standard principal components analysis, pertain to the Cartesian axes. The two primary dimensions typically capture most data variation ([95,96]). This approach dynamically identifies diverse relationships at the meso-level for the Italian regions, as presented in Figure 5, panels from a) to f). All these decision-making units are represented by points in four quadrants, as outlined in the figure caption. Arrows represent the socio-economic and environmental indicators as previously defined; dotted arrows denote a negative correlation or dissimilar impact. Notably, 2004 reflects the parametric construct, given the data availability.

For a comprehensive overview, Figure 6 from panel a) to panel f) provides a combination of decision-making units (points), indicators (arrows) and more defined clusters (circles).

The first remarkable feature is the high correlation between renewable energy demand (RE_C) and supply (RE_G) in line with the parametric results (RQ1). However, while the impact in 2004 was higher in Valle d'Aosta (VA) and Trentino (TR), over time, Valle d'Aosta denotes the highest impact. This outcome is proved consistently in all years under investigation (bottom left quadrant).

As a comparison of the main economic indicators, a convergence emerged in 2004 amongst specific clusters of Italian regions. The southern regions (top right quadrant) suffer a structural socio-economic lagging (*Y, HCF, HCA*), denoted by the dotted arrows. The centre regions (bottom right quadrant), especially Lombardia and Liguria, experienced more dynamic human capital formation (*HCF*) and accumulation (*HCA*). Trentino and Valle d'Aosta are positioned in the bottom left quadrant of the biplot, indicating a relatively high per capita disposable income (*Y*). However, while they form a cluster, there is a discernible distance between the two regions, implying dissimilarities.

The multivariate biplot analysis expands the standard economic framework by adding extra mediators and controls (available from 2012). Once again, well-defined clusters mirror the south (bottom right quadrant) and the centre-north of the country (top left quadrant). In all years, Trentino and Valle d'Aosta are characterised by high RE_C and RE_G: these two regions appear dissimilar to the other clusters.

As common features, in all the years under investigation, Trentino is the region that denotes the highest satisfaction with the environment (*ENSA*). Notably, this outcome is consistent with the fact that this region, formed by the Autonomous Provinces of Bolzano and Trento, has committed since 2009 to implementing local actions to reduce CO_2 emissions by at least 20 per cent by 2020. As part of this commitment, a basic emissions inventory and the Sustainable Energy Action Plan were drafted ([97]). In contrast, people living in southern regions are the least satisfied with the environment. These findings combined with the stable and strong negative correlation between ENSA and illegal building (IB) that affects the southern regions, with a prevalence in Campania, Calabria and Molise ([35]). Furthermore, in the last years of observations, the illegal land use also directly impacted other regions such as Puglia and Basilicata ([36]).

These land abuses, combined with extreme weather events in Italy, have become less predictable and have increased in intensity ([38,39]). Indeed, the results show the population's dissimilar perceptions of climate change (*PCC*). While a negative perception was

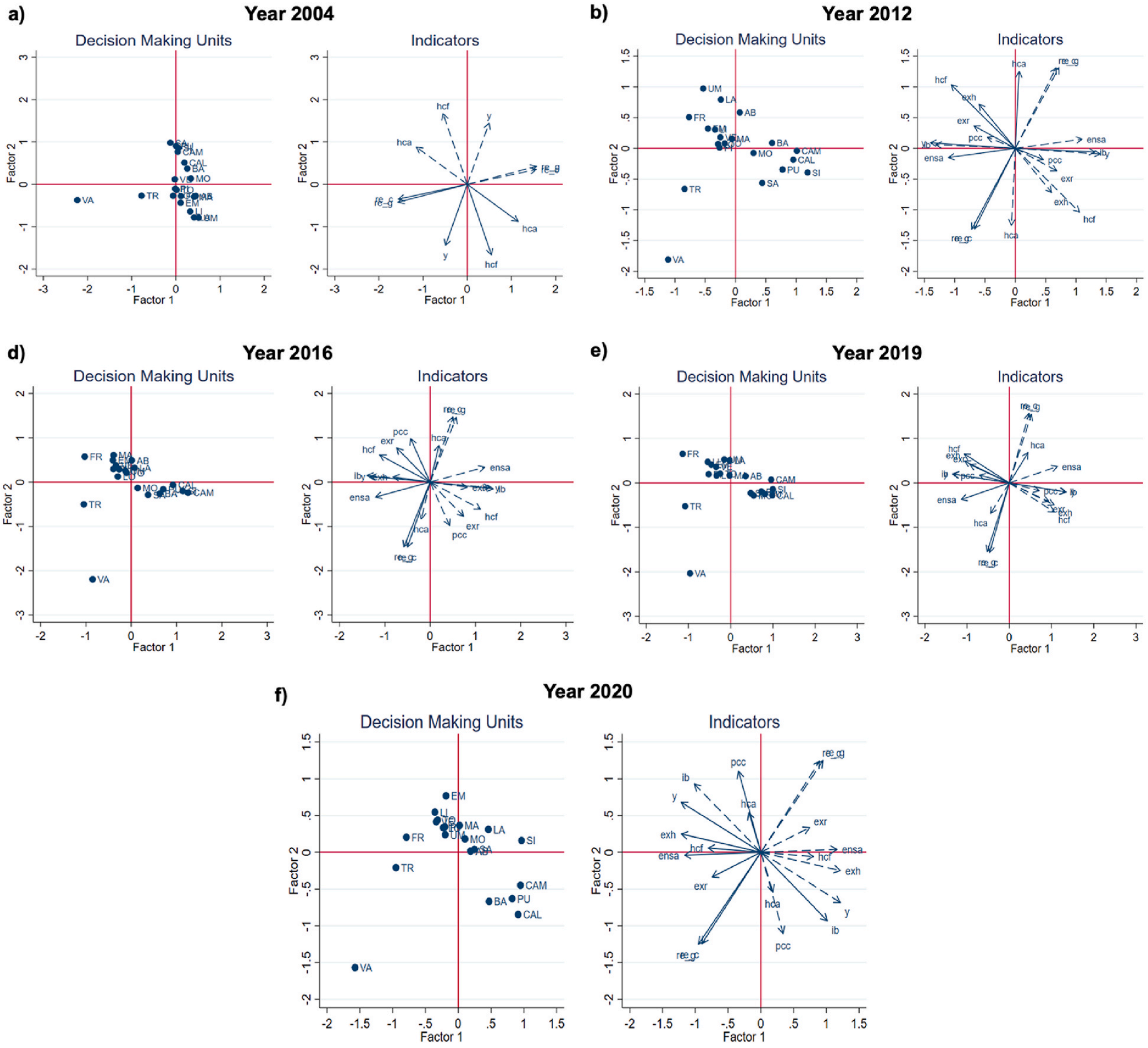

Fig. 5. Panels a) to f) present biplots of Italian regions (decision-making units as points) and indicators (arrows) for 2004, 2012, 2016, 2019, and 2020. Regions are plotted on the left, and indicators on the right. *Notes:* Quadrant definition: North-West: Liguria=LI, Lombardia=LO, Piemonte=PI, Valle d'Aosta=VA; North-East: Emilia-Romagna=EM, Friuli-Venezia-Giulia=FR Trentino=TR, Veneto=VE; Centre: Lazio=LA, Marche=MA, Toscana=TO, Umbria=UM; South: Abruzzo=AB, Basilica=BA, Calabria=CAL, Campania=CAM, Molise=MO, Puglia=PU, Sicilia=SI, Sardegna=SA.

more evident in the south of the country (bottom right quadrant) in 2012, in the following years, *PCC* was linked to more days of extreme rain (*EXR*) and heat (*EXH*), with remarkable impacts in the centre and north of the country.

6. Discussion

The study addresses three primary research questions using a meso-level panel dataset covering Italian regions from 2004 to 2020. Parametric analysis, rooted in the Solow-Swan and KLEM models, provides robust evidence of market equilibrium between renewable energy supply and demand in the short and long run (RQ1). Understanding the simultaneous relationship between demand and supply holds significant implications for policymaking, market interventions, and business strategies. Policymakers can enhance the effectiveness of demand-side policies through fiscal stimuli such as taxation or incentives. On the supply side, setting achievable targets and implementing tailored policies such as production subsidies can stimulate innovation and growth in the renewable energy sector. Public support for R&D can further reduce renewable energy production costs and foster knowledge-sharing, technology transfer, and advancements in energy solutions at the EU level ([43]). In this regard, Hao and Shao [26] found that public policies encouraging renewable sources garner greater support for the green transition and reduce reliance on fossil fuels.

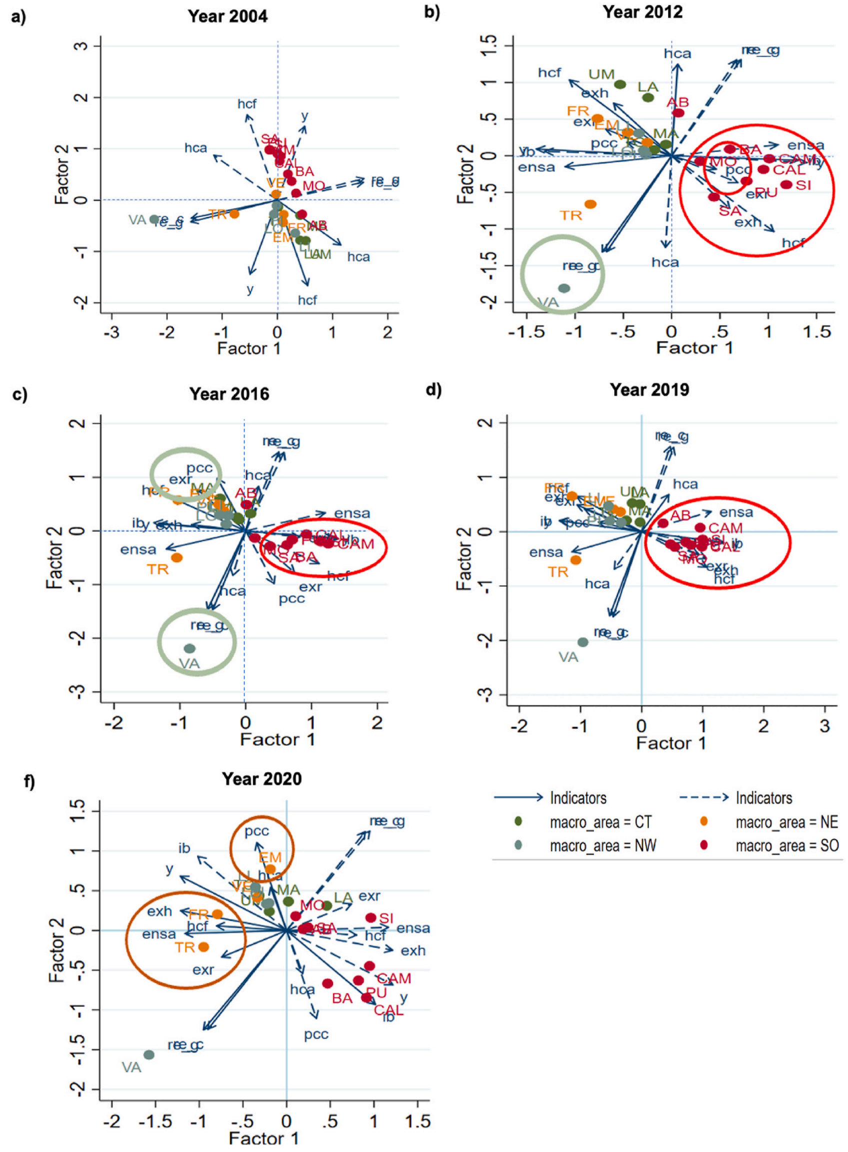

Fig. 6. Panels a) to f) present joint biplots of Italian regions and macro areas (decision-making units as points) and indicators (arrows) for 2004, 2012, 2016, 2019, and 2020. *Notes:* For acronyms. see Figure 5 caption. 2004: Total explained variance = 85 % (Factor 1 = 48 %; Factor 2 = 37 %). 2012: Total explained variance = 58 % (Factor 1 = 34 %; Factor 2 = 24 %). 2016: Total explained variance = 64 % (Factor 1 = 37 %; Factor 2 = 27 %). 2019: Total explained variance = 67 % (Factor 1 = 45 %; Factor 2 = 22 %). 2020: Total explained variance = 57 % (Factor 1 = 37 %; Factor 2 = 20 %).

Human capital accumulation is consistently pivotal in the renewable energy transition (RQ2)**.** These findings highlight the importance of considering proactive strategies and investments in human capital for promoting sustainable energy practices ([51,61,98]). Educated and wealthier individuals, particularly among younger demographics, are more environmentally conscious, as highlighted by Ali et al. [40]. Thus, public policies facilitating expanded education can be crucial in fostering sustainable energy practices. In this context, renewable energy communities can promote the implementation of sustainable and economically efficient projects while protecting fragile ecosystems ([3,60]).

Non-parametric biplot analysis offers dynamic insights into di-/convergence among regions and the effectiveness of public and private policies over time**.** Notably, Italian regions exhibit remarkable heterogeneity (RQ3), Valle d'Aosta and Trentino emerging as leaders in renewable energy development, demonstrating a noteworthy gap with the other regions (see Figure 4). This outcome, aligned with Ali et al. [59], reinforces the pressing need to prioritise human capital development, enhance economic opportunities, and reduce regional disparities (RQ2).

Furthermore, the negative correlation between perceived environmental satisfaction and illegal building in southern regions highlights the necessity for stronger regulations and enforcement to combat harmful land use practices. Extreme and unpredictable weather conditions further strain the economy, necessitating policies to reduce inequality and foster inclusive development in alignment with the SDGs ([13]). Institutional quality is pivotal in enhancing the renewable energy transition, as evidenced in Italy by Huihui et al. [50].

From a methodological standpoint, the parametric specification presents challenges such as multicollinearity due to high correlations and possible inefficiency in estimation due to a relatively small sample size. This important issue has been further addressed in Appendix B, where demand and supply are estimated as separate frameworks. Conversely, while offering dynamic insights, the biplot approach is limited by its cross-sectional dimension and does not account for potential causalities. Additionally, two-dimensional visualisations may lead to information loss and biased data representations. Hence, integrative methods are valuable for understanding complex phenomena and dynamics and mitigating potential procedure issues.

7. Conclusion and policy implications

This study significantly contributes to the existing literature by analysing the complex interrelationships between renewable energy demand and supply within a meso-level setting. Methodologically, a parametric analysis based on the Solow-Swan and KLEM models explored the equilibrium between renewable energy supply and demand across Italian regions. Additionally, non-parametric biplot analysis provided insights into regional heterogeneities and policy effectiveness.

As emphasised by the International Renewable Energy Agency, sustaining the energy transition necessitates policies that facilitate job opportunities for those facing job displacement risks in lagging economic sectors, especially in fossil fuels ([99]). Simultaneously, policies should actively promote the accumulation of human capital, including through life-long learning education. In this context, various promising initiatives are already underway, encompassing vocational training, learning programmes, and advancements in information and communication technologies ([100]). The Italian National Recovery and Resilience Plan ([101]), issued in May 2021, underlines commitment to these objectives.

Findings underscored the importance of long-term sustainability strategies and human capital development in fostering renewable energy transitions. The empirical evidence highlighted significant regional heterogeneity in renewable energy adoption, with Valle d'Aosta and Trentino emerging as leaders. These insights are crucial for guiding policy interventions aimed at balancing regional disparities and promoting sustainable energy practices nationwide ([1]). These results also reveal the significance of prioritising infrastructure implementation as an integral component of comprehensive sustainable development actions. By addressing regional socio-economic disparities and fostering successful energy transition, policymakers can strengthen the foundation for a resilient economy and a sustainable future. It is imperative that future energy policies continually monitor and implement renewable energy and environmental strategies to ensure the establishment of balanced and sustainable systems in all Italian regions. These policies should encompass all technical, and socio-economic dimensions related to deploying renewable energy systems, while frameworks for creating local hubs should be envisioned to foster knowledge and best practice exchange.

Additionally, as addressed by the biplot framework, integrating policies focused on resilience to extreme weather and disaster risk management is essential. Investments in resilient infrastructure, early warning systems, and inclusive development policies that reduce inequality are critical for sustainable growth. Strengthening institutional quality and governance is also necessary to enable pro-environmental investment. Policymakers should enhance a harmonious development between anthropic activities, landscapes and ecosystems, especially in fragile and highly-quality settings ([36,37,56]). Public-private partnerships should be encouraged to leverage private sector expertise and resources, driving innovation and efficiency in renewable energy projects with wider involvement of local communities ([5,7,44,102,103]).

Although this study contributes to the understanding of renewable energy transitions in Italy, it also sets a foundation for broader international comparisons and methodological advancements in renewable energy research. Comparative studies across diverse national contexts could provide deeper insights into how varying regulatory frameworks, economic structures, and cultural factors influence renewable energy transitions.

Several limitations of the present research should be acknowledged together with venues for future research. Although this study provides valuable empirical evidence on the simultaneity condition of renewable energy demand and supply, the lack of energy prices at a regional level represents a limitation in fully capturing the equilibrium dynamics within the market: this can be further addressed by country-based comparisons or typically in a monopolistic market regime without price discrimination.

Moreover, exploring alternative methodologies and integrating new indicators could more comprehensively capture the renewable energy system's multifaceted nature. Innovations in data collection methods, such as integrating qualitative approaches or advanced statistical techniques such as machine learning, could enhance the depth and accuracy of future analyses. Besides, spatial and longitudinal studies could deepen energy transition dynamics and highlight regional interdependencies and policy effectiveness. By extending the analysis over longer time horizons and examining spatial variations within regions, researchers can better understand how local factors interact with broader policy initiatives. These extensions would highlight regional disparities in renewable energy adoption and inform targeted policy interventions that address specific regional challenges and opportunities.

CRediT authorship contribution statement

Mattia De Rosa: Writing – review & editing, Writing – original draft, Validation, Funding acquisition, Conceptualization. **Marta Meleddu:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Manuela Pulina:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Data availability statement section

Table 1.A provides details and links on the sources of the indicators used in the analyses and their definitions. The complete dataset is available upon request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Mattia De Rosa reports financial support was provided by European Commission. No conflicts If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table 1.A
Indicators, definitions, sources.

Indicators	Label	Definition	Source	SDG
Standard Solow framework				
Renewable energy demand	RE_C	Per capita consumption of renewable energy in kilowatt-hours	ISTAT elaboration on Terna data (2004–2020) https://www.terna.it/it/sistema-elettrico/statistiche/pubblicazioni-statistiche	Goal 7 – Ensure access to affordable, reliable, sustainable, and modern energy
Renewable energy supply	RE_G	Per capita supply of renewable energy in kilowatt-hours	Authors’ elaboration on Terna data (2004–2020) https://www.terna.it/it/sistema-elettrico/statistiche/pubblicazioni-statistiche	Goal 7 – Ensure access to affordable, reliable, sustainable and modern energy
Income	Y	Disposable income per capita	ISTAT elaboration on national accounts data (2004–2020) http://dati.istat.it/https://www.istat.it/it/benessere-e-sostenibilit%C3%A0/la-misurazione-del-benessere-(bes)/gli-indicatori-del-bes	Goal 10 – Reduce inequality within and among countries
Overeducation	HCA	Share of overeducated employees with a university education	ISTAT elaboration on labour market data (2004–2020) http://dati.istat.it/https://www.istat.it/it/benessere-e-sostenibilit%C3%A0/la-misurazione-del-benessere-(bes)/gli-indicatori-del-bes	Goal 4 – Quality education
High school degree	HCF	Share of 25–64-year-olds who hold a high school degree (at least ISCED 3)	ISTAT elaboration on labour market data (2004–2020) http://dati.istat.it/https://www.istat.it/it/benessere-e-sostenibilit%C3%A0/la-misurazione-del-benessere-(bes)/gli-indicatori-del-bes	Goal 4 – Quality education
Further mediating and controls within the biplot				
Satisfaction with the environment	ENSA	Percentage of those who are satisfied with the environment	ISTAT survey on aspects of daily life and environment (2012–2020) http://dati.istat.it/https://www.istat.it/it/benessere-e-sostenibilit%C3%A0/la-misurazione-del-benessere-(bes)/gli-indicatori-del-bes	Goal 11 – Sustainable cities and communities
Perception of climate change	PCC	Percentage of those who are concerned about climate change (%)	ISTAT survey on aspects of daily life and environment (2012–2020) http://dati.istat.it/https://www.istat.it/it/benessere-e-sostenibilit%C3%A0/la-misurazione-del-benessere-(bes)/gli-indicatori-del-bes	Goal 13 – Take urgent action to combat climate change and its impacts
Extreme rain	EXR	Number of days	Copernicus, European Union’s Earth Observation Programme, Gridded dataset climate analysis, ERA5 hourly data (2012–2020) https://www.istat.it/it/archivio/285730	Goal 13 – Take urgent action to combat climate change and its impacts

(continued on next page)

Table 1.A (*continued*)

Indicators	Label	Definition	Source	SDG
Extreme heat	EXH	Number of days	Copernicus, European Union's Earth Observation Programme, Gridded dataset climate analysis, ERA5 hourly data (2012–2020) https://www.istat.it/it/archivio/285730	Goal 13 – Take urgent action to combat climate change and its impacts
Illegal building	IB	Amount of new illegal housing over 100 authorisations by town council (%)	ISTAT elaboration on Cresme data (2012–2020) https://www.istat.it/it/benessere-e-sostenibilit%C3%A0/obiettivi-di-sviluppo-sostenibile/gli-indicatori-istat	Goal 11 – Sustainable cities and communities

Table 2.A
Descriptive statistics (the all sample).

Indicators	Obs	Mean	Std. Dev.	Min	Max	p1	p99	Skew.	Kurt.
RE C	340	5,146.6	13,884.0	16.3	85,957.9	53.2	78,197.4	4.1	20.0
RE G	340	3,106.1	5,363.9	66.7	28,882.5	129.4	27,387.9	3.4	14.1
Y	340	17,568.2	3,462.2	11,363.1	24,059.6	12,139.1	23,224.2	−0.2	1.6
HCA	340	21.7	4.4	11.2	33.0	12.3	31.7	−0.0	2.54
HCF	340	57.1	7.6	39.3	72.0	40.3	71.0	−0.2	2.16
IB	340	20.6	18.5	1.8	68.3	1.8	67.2	1.0	2.8
ENSA	320	73.5	9.0	36.2	90.7	47.6	89.6	−0.8	3.8
EXH	200	20.0	11.2	0.0	70.0	0.0	60.5	1.3	6.1
EXR	200	0.9	1.1	0.0	6.0	0.0	5.0	1.7	6.5
PCC	180	64.4	4.9	53.1	77.5	53.2	77.1	0.2	2.6

Table 3.A
Pairwise correlations (the all sample).

Indicators	RE_C	RE_G	Y	HCF	HCA	IB	ENSA	EXH	EXR	PCC
RE_C	1									
RE_G	0.976***	1								
Y	0.230***	0.273***	1							
HCF	−0.028	0.021	0.647***	1						
HCA	−0.201***	−0.204***	−0.014	0.672***	1					
IB	−0.052	−0.053	−0.314***	−0.043	0.246***	1				
ENSA	0.394***	0.464***	0.444***	0.411***	0.052	−0.184***	1			
EXH	0.166**	0.188***	0.378***	0.189***	−0.175**	−0.277***	0.267***	1		
EXR	0.166**	0.188***	0.378***	0.189***	−0.175**	−0.277***	0.267***	1.000***	1	
PCC	−0.084	−0.072	0.245***	0.338***	0.330***	0.141*	0.062	0.002	0.002	1

Note: Statistical significance ***p < 0.01, **p < 0.05, *p < 0.1.

Appendix B

This appendix provides a comprehensive overview of the methodology employed to estimate the demand and supply equations as separate frameworks. The demand equation is formulated according to the standard function as follows (Apergis and Eleftheriou, 2015):

$$RE\_C = f\ (Y, HCA)\ (1)$$

Similarly, the supply equation is constructed using the classical KLEM function:

$$RE\_G = f\ (GDP, K, HCA)\ (2)$$

Table 1.B. provides a detailed account of the new economic indicators for analysing the supply framework. It outlines their definitions and the respective sources utilised in the study.

Table 1.B
Indicators, definitions, sources.

Indicators	Label	Definition	Source	SDG
Standard framework				
Gross domestic product	GDP	Per capita real GDP, national currency per head, constant prices (EURO, SNA, 2008) by NUTS 2 regions	OECD (2004–2019) https://ec.europa.eu/eurostat/databrowser/view/nama_10r_2gdp/default/table?lang=en	Goal 10 – Reduce inequality within and among countries
Physical capital	K	Real gross fixed capital formation by NUTS 2 regions	OECD (2004–2019) macrotrends.net, Eurostat https://ec.europa.eu/eurostat/databrowser/view/nama_10r_2gfcf/default/table?lang=en	Goal 10 – Reduce inequality within and among countries

Table 2.B includes the main statistical features, highlighting key metrics essential for assessing the reliability of the analysis.

Table 2.B
Descriptive statistics (the all sample).

Variables	Obs	Mean	Std. Dev.	Min	Max	p1	p99	Skew.	Kurt.
GDP	320	27,883.75	7,339.14	16245	41,812.7	16,550	40,819	0.117	1.823
K	320	5,303.378	1,689.92	2,370.72	10,649.1	2,493.8	9,833	0.507	3.019

Table 3.B. presents the pairwise correlations for all the indicators under analysis. As expected, a substantial correlation of 91 per cent is observed between *GDP* and *K*. This high correlation raises concerns regarding potential multicollinearity, which can potentially impact the robustness and reliability of the regression analysis.

Table 3.B
Pairwise correlations (the all sample).

Indicators	RE_C	RE_G	GDP	K	HCF	HCA
RE_C	1					
RE_G	0.976***	1				
GDP	0.354***	0.402***	1			
K	0.445***	0.512***	0.907***	1		
HCF	−0.028	0.021	0.464***	0.318***	1	
HCA	−0.201***	−0.204***	−0.248***	−0.334***	0.672***	1

Based on the methodology proposed in the paper, Table 4.B presents full results for the two specifications.

Table 4.B
Long-run renewable energy demand (RE_C) estimation.

Models	Y	HCA
LR coefficients (N=320)	0.430	**0.870*** **

Notes: Long-run (LR) coefficients; ***p < 0.01, **p < 0.05, *p < 0.10.

Table 5.B
Long-run renewable energy generation (RE_G) estimation.

Models	GDP	K	HCA
LR coefficients (N=280)	**0.154*** **	−0.628	**2.048*** **
LR coefficients (N=280)	**−1.104*** **	/	**1.588*** **

Notes: LR coefficients; ***p < 0.01, **p < 0.05, *p < 0.10.

The findings validate the pivotal role of human capital accumulation in driving the adoption of renewable energy sources. However, regarding the supply function, the analysis reveals a concerning multicollinearity issue due to a very high correlation in the full equation, as already stated. Interestingly, the second equation presents divergent results, particularly proved by a change in the sign of the *GDP* coefficient. Notably, the latter outcome aligns with the findings obtained from the joint demand-supply framework. Hence, this empirical analysis suggests the presence of substitution effects in the Italian economy and indicates that the transition towards renewable energy sources is still underway.

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