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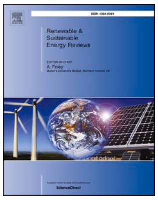

Spatiotemporal influencing factors of energy efficiency in 43 european countries: A spatial econometric analysis

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ABSTRACT

The increase in consumption and the increase in the use of resources linked to increasing human activity puts both energy security and sustainability at risk, which has led to a global restructuring of the policy agenda to ensure and integrate environmental well-being through channels such as energy efficiency (EE). Bearing this in mind, the objective of this research is to analyze the relationship between energy efficiency, renewable energy and financial development? For this reason, an analysis is conducted, which includes energy intensity measured by the Gross Domestic Product (GDP) per unit of energy use as a measure of efficiency for 43 European countries (period 1990–2019). The objective is to observewhether the use of renewable energy and the investments being made are driving economies towards higher EE and sustainable economic growth. The present study leverages on spatial econometrics models, which allow for the analysis of spillovers between economies. The results obtained allow us to observe the existence of spatial autocorrelation of EE between countries in Europe. Secondly, it is observed that the use of renewable energies promotes EE in neighbouring economies, as well as in the return effect. On the other hand, financial development shows that only the institutional component favours EE by generating a return effect on the economy itself, while the stock market component deteriorates the EE of neighbouring economies and on the same economy. Therefore, the analyzed data shows that the use of renewable energies promotes the improvement of EE and that being close to countries that replace the use of traditional energies with alternative sources has a positive effect on national EE. These mechanisms would allow policy makers to develop mechanisms for greener and more sustainable development, while encouraging efficient energy use.

1. Introduction

The International Energy Agency (IEA) states that, "in developing economies, the continuous growth in energy use is closely related to the growth of modern sectors such as industry, motorized transport, and urban areas, but energy use also reflects climate, geographic and economic factors (such as the relative price of energy)" [1]. In addition, the IEA report states that "the use of energy has grown rapidly in low- and middle-income economies, but high-income economies still use almost five times more energy per capita" [1]. As a result, public administrations of most countries in the world they acquire a great awareness of the need for use more efficient energy sources. Improving

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Abbreviations: (EE), Energy Efficiency; (GDP), Gross Domestic Product; (IEA), International Energy Agency; (STIRPAT), STochastic Impacts by Regression on Population, Affluence and Technology; (SDG), Sustainable Development Goal; (EU), European Union; (OECD), Organization for Economic Co-operation and Development; (RE), Renewable Energy; (EDI), Export Diversification Index; (URB), Urbanization; (SLM), Spatial Lag Model; (SEM), Spatial Error Model; (SDM), Spatial Durbin Model; (MLE), Maximum Likelihood Estimation; (LR), Likelihood Ratio; (LM), Lagrange Multiplier; (FI), Financial Institutions development; (FM), Financial Market development; (LISA), Local Indicators of Spatial Association.

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EE is often the cheapest and most available means of improving energy security and reducing environmental degradation [2]. In Europe, EE constitutes an important part of achieving carbon neutrality by 2050 [3]. In addition, initiatives such as the European Green Pact, Objective 55 of the Commission and the Paris Agreement aim to improve the relationship between energy obtaining and consumption.

In this regard, mechanisms such as renewable energies and financial development could provide a solution for sustainable energy consumption. The research carried out aims to answer the question on whether an inclusion of renewable energies and financial development would imply an improvement or a setback in EE. To this end, this investigation used the dimension energy intensity, which is a usual measure of EE, to capture the impact of the aforementioned indicators. This was done in the context of the theoretical components of the STochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model such as population, affluence and technology. Regarding the literature, there are studies that have examined the relationship between these components separately, in addition to applying models that only consider the temporary behaviour of efficiency. On the one hand, there are studies that link renewable energies as a means for reducing energy intensity and facilitating the adoption of cleaner fuels [4–7]. It is also a mechanism by which governments promote energy security [8,9]. Likewise, financial development could encourage research and development, which would serve as a bridge to improve both the financial infrastructure and their communication channels [10–13]. In this context, this investigation focuses mainly on European economies, since despite implementing mechanisms for a transition to renewable energies, there is still a high dependence on energy imports [14].

The study fills this gap in the literature on this topic. In this research, estimating the effect of the use of renewable energy and financial development on EE in European economies. The study aims to analyze spillover effects in 43 European countries from 1990 to 2019 b y using spatial models. This study is original and differs from previous ones in several ways. Firstly, it contributes to the analysis of efficiency over a larger sample, which considers both highly energy-dependent economies and economies with a high production and supply export capacity in Europe. Thus, the study broadens the global debate on the use of primary energy from fossil fuels and its energy transition to cleaner sources. Secondly, Secondly, in this research, spatial models are applied for the study of the stated objective. This approach allows to determine the spatial correlation of EE between the countries under study. In addition, these models make it possible to identify whether the total effect responds to an indirect or spillover behaviour, or to a direct or return effect. This perspective was not followed in previous studies that studied the relationship between EE, renewable energy use and financial development. The main reason for using this perspective is to address the spatial behaviour of EE on a region, even more so in an area where there is a high exchange of activities and political agreements. The results highlight the need to prioritize the transition to the use of renewable energies also called clean energy, as well as the implementation of policies and mechanisms that accelerate this process. On the other hand, it is important for the development process of the financial sector to consider the high energy consumption that comprises the stock market component, so as to prioritize the efficient use of energy and promote a more sustainable growth process.

Following this, this document is organized into six sections. Section 2 reviews previous research linking efficiency with analysis factors. Section 3 presents models and empirical methods used. Section 4 presents the data sources and descriptive statistics. The analyses of the findings on the importance of renewable energies, economic production, urbanization, financial market and institutional development, export diversification on EE in Europe are collected in section 5. Finally, the last section discusses the conclusions.

2. Literature review

In order to meet Sustainable Development Goal (SDG) 7, economies should consider redoubling their efforts to improve their EE. According to Adom et al. [15], growth and EE are closely related, so much so that unsustainable growth can affect efficient energy consumption, just as improvements in EE would trigger economic growth. In fact, shifting from an economic structure based on capital-intensive energy supply sectors to relatively labour-intensive manufacturing and services sectors improved Canada's EE [16]. Therefore, an improvement of the industrial structure plays an important role in the EE process [17]. Also, with respect to income level, economic growth decreases energy intensity for the lower-middle income group of countries, in other words, it decreases energy consumption, thereby improving efficiency levels by shifting from a low-income to a high-income economy [18–20]. As for Marques et al. [21], they suggest that the average growth of the industrial sector of European economies is leading to higher EE provided that energy prices are controlled.

Focusing on Europe, Makridou et al. [22] assess EE trends of five industries that use energy intensively. These authors showed that industrial EE is mainly due to technological improvement, while "high electricity prices, energy taxes and the market share of the largest generator in the electricity market have a negative effect on EE" [23,24]. Also, Mahmood & Ahmad [25] show that energy intensity decreases significantly when economies grow, stability and, in some cases, the decline in the European population. On the other hand, Pan et al. [26] (p.12,878) argue that if the added value of domestic manufactures of 35 European economies "*accounts for a higher percentage of GDP, it will have a negative impact on the efficiency of energy use. In addition, the same authors argue that when the domestic price level is high, price fluctuation will increase the energy cost in economic activityes, which will further reduce EE performance*".

Furthermore, sustainable economic progress requires energy sources renewable and promotes everything related to energy security (global warming and climate change) [8,9]. Along these lines is the work of Li et al. [6] and Yang et al. [7], who state that technical innovation can improve the total EE of China's ecological factors, provided that there is environmental regulation involved and efficient capital allocation, respectively. Hence the interest of countries in promoting their energy security in different ways, "*such as reducing energy intensity through increased investment in advanced technologies, which is one of the most efficient ways to reduce energy consumption and production costs*" [27] (p.156).

According to Zhu et al. [4] and Kucher & Prokopchuk [5], energy diversification promotes the use of alternative sources, especially in economies with scarce resources, by increasing the use of renewable energies and reducing the share of fuel generation fossils, which promotes both the reduction of emissions and the improvement of EE. This is in a scenario where the European Union (EU) is among the most vulnerable countries/unions due to its high dependence on energy imports and scarcity of energy reserves [14]. In this same line, Kolosok et al. [28] argues that in European countries, the share of energy from renewable sources is positively correlated with all EE indicators, except energy productivity. For South Asian economies, the result is similar, since by increasing the share of renewable energy, they reduce "*the intensity of energy use, which facilitates the adoption of cleaner fuels for domestic use and reduces carbon dioxide emissions*" [21].

Urbanization, which brings with it the increase in industrialization and economic development, is the result of migration of the population from rural to the cities (urban areas), with a change in consumer behaviour and lifestyles, as well as an increase in energy-intensive industries [29]. However, "*urbanization is also considered a complex process accompanied by technological advantages and economies of scale that can improve EE and decrease overall energy use*" [29] (p.3). Therefore, the net effect of urbanization on EE is unclear and requires further empirical investigation from other per spectives. Mrabet et al. [30] (p.837) evidence the existence of a “*positive impact of urbanization on energy demand from traditional sources, both in developed and emerging countries, while it has a higher elasticity in the first group*”.

In this same line of analysis, Liu et al. [31] and Lv et al. [32] present heterogeneous effects of urbanization on the EE of the provinces of China. The first study shows that urbanization limits EE at the spatial level and the second study finds an average effect on panels, which encourages the efficient use of energy. A similar scenario is seen in Organization for Economic Co-operation and Development (OECD) economies, where urbanization limits the challenges to improve EE [12]. On the other hand, Adom [33] argues that in Africa, energy consumption decreases due to the economies of scale that arise from intense urbanization. Therefore, the author proposes that in order to maintain the benefits that are obtained from the economies of scale derived from the high urbanization, maintaining continuous levels of investment in infrastructure by the government should be prioritized.

Finally, both financial development and trade openness could encourage research and development, as well as infrastructure technology, where these expenses further help to achieve EE and reduce energy demand [34–36]. In this regard, Bashir et al. [12] suggest that financial development policies should be aimed at encouraging credit lines that finance I + D activities to produce innovative products. Thus, the study developed by Atta Mills et al. [11] suggests that Belt & Road (B&R) associated economies perceive a positive and significant type of effect of financial development, which becomes insignificant as it increases, on EE. However, the sole effect of financial development does not improve EE levels, since it is conditioned by the levels of government transparency and corruption control [37].

On the other hand, Zhao & Lin [38] argue that imports have a higher degree of impact on EE than textile exports in China, which is conditioned by the commercial activities of this sector of the industry. In a global context, exports have an advantage in improving EE levels by enabling the relationship towards economies with advances in energy-saving technologies [37]. However, in developing economies such as China, the efficiency-enhancing effect on exports is not visible and, like foreign direct investment, it decreases the EE of neighbouring provinces [39]. In addition, Alfonso et al. [40] show that other factors such as the energy security and carbon intensity of countries largely condition trade openness, which depending on the level of trade openness, each of these would generate favorable or unfavourable conditions for EE.

3. Theoretical framework and data

3.1. Theoretical framework

In this investigation, the range of factors influencing EE is explored according to the IPAT model developed by Ehrlich & Holdren [41]. It shows that I=P*A*T. IPAT model postulates that the key forces behind environmental impacts (I) are the population (P), affluence (wealth) (A) and technology (T). The model is shown in the equation below:

$$I_{i,t} = aP_{i,t}^{b}A_{i,t}^{c}T_{i,t}^{d}e_{i,t} \tag{1}$$

Where, “I denotes environmental impact P,A,T denote population, affluence and technology, respectively a denotes the constant terms, b,c and d are the estimated parameters e is the random disturbance term”.

However, this model has limitations, according to Hua et al. [42] and Pyzheva et al. [43] “*cannot deal with non-monotonic and non-propositional changes in variables*”. Therefore, Dietz & Rosa [44] in a new model called STIRPAT model, included the factors of economic scale, energy structure, and environmental regulation. By using natural logarithms, “*the STIRPAT model can be converted to a convenient linear specification for panel estimation*” [45] (p0.249):

$$\ln I_{i,t} = a_0 + b\ln P_{i,t} + c\ln A_{i,t} + d\ln T_{i,t} + e_{i,t} \tag{2}$$

Similar to Wei et al. [39], it presents an improved form of the STIRPAT model, including *EE* as an alternative environmental impact factor to other investigations [46,47]. On the other hand, this model ignores other important factors that influence EE, such as financial development and trade openness. These factors are included in equation (2) in order to further analyze their effect on the environment. Thus, the STIRPAT model is modified by adding financial development and trade openness to the set of factors, which results in the following:

$$\ln\left(EE_{i,t}\right) = a_0 + b\ln\left(URB_{i,t}\right) + c\ln\left(GDP_{i,t}\right) + d\ln\left(RE_{i,t}\right) + fCV_{it} + \mu_t + \varepsilon_{it} \tag{3}$$

Where, EE measured by GDP per unit of energy usage or energy intensity GDP per capita. URB = the total urban population.

Dietz and Rosa [44] (p.176) propose, “*total urban population and GDP* per capita *measure the impact of demographic and economic factors*”. Renewable Energy (*RE)* represents the technological component derived from alternative energy production; *FI* and *FM* represent financial development, considering two components, institutional and market, respectively; and finally trade openness measured by the Export Diversification Index *(EDI)*. These additional factors to the STIRPAT model are included in CV as control variables as determinants of EE (these variables are suggested in previous studies); μ_i and ε_{it} is the individual fixed effect and the standard error term.

3.2. Methodology

3.2.1. Spatial autocorrelation: global Moran’s I

Spatial models have the need to establish the effect of spatial agglomeration in EE as a preliminary step to the estimates [48]. Therefore, it is essential to apply tests that determine spatial correlation. For this reason, Moran’s I and Geary’s C statistics are used to determine the direction and degree of spatial autocorrelation. These are obtained according to Equations (2) and (3), respectively.

$$I_i = \frac{\mathrm{n}}{s}\,\frac{\sum_{i}^{N}\sum_{j}^{N}W_{i,j}\left(x_{i,t}-\overline{x_t}\right)\left(x_{j,t}-\overline{x_t}\right)}{\left[\sum_{i}^{N}\left(x_{i,t}-\overline{x_t}\right)^2\sum_{i}^{N}\sum_{j}^{N}W_{i,j}\right]} \tag{4}$$

Where, “n represents the number of cross-sections , s is the sum of all the elements of the preferred weight matrix (w)”.

$$C_i = \frac{(n-1)\sum_{i}\sum_{j}W_{ij}\left(x_i-\overline{x}\right)\left(x_j-\overline{x}\right)}{2\left(\sum_{i}\sum_{j}W_{ij}\left(x_i-\overline{x}\right)^2\right.} \tag{5}$$

This study considered a queen-type matrix for spatial analyses. Regarding the statistics, they test the null hypothesis of spatial randomness. The value for Moran’s I can range from 1 to −1 (values above 0 represent positive spatial autocorrelation and below 0 negative. Meanwhile, for Geary’s C, values less than 1 represent increasing positive spatial autocorrelation and negative, for values greater. In both tests, the values 0 and 1 represent spatial randomness.

3.2.2. Spatial econometric specifications

Elhorst [49] states that there are several models proposed by experts that allow to explore the spatial interaction effects between the dependent and independent variables. It is important to mention that the most widely used models in the spatial literature are: the Spatial Lag Model (SLM), the Spatial Error Model (SEM), it explaining spatial dependence in the error terms and (SDM) the spatial Durbin model that is developed from the Spatial Autoregressive Model (SAR).

The theory about the spatial lag model indicates that this is applied whenever between the dependent variable there is an endogenous interaction. Variable that on the other hand, is the most appropriate when the objective is to determine the existence of spatial interaction and to quantify its strength. Equation (6) represents the specification of SLM.

$$y_{it} = \rho \sum_{j=1}^{N} w_{ij} y_{it} + \beta x_{it} + \mu_i + \xi_t + \varepsilon_{it} \tag{6}$$

Where, “*i* is an index for the cross-sectional dimension corresponding to spatial units, with $i = 1,...,N t$ is an index for the time dimension corresponding to the time period, with $t = 1,...,T y_{it}$ denotes the dependent variable $\sum_{j=1}^{N} w_{it} y_{it}$ denotes the endogenous interaction effects between the dependent variable, in other words, the spatial lag term of the dependent variable w_{ij} is an element of the $N \times N$ matrix describing the spatial configuration or arrangement of the units x_{ij} denotes the K -dimensional independent variables β represents the estimated parameters of the independent variables ρ is the spatial autoregressive coefficient μ_i denotes the spatial specific effect ξ_t denotes the time-specific effect ε_{it} is a disturbance term”.

Asimismo, cuando la dependencia espacial responde a través de variables omitidas, se utiliza el modelo de rezago espacial (SEM). The SEM is specified in equation (7) and in the model an error process of different regions that show spatial covariance is used.

$$y_{it} = x_{it}\beta + \mu_i + \xi_t + u_{it}, u_{it} = \lambda \sum_{j=1}^{N} w_{ij} u_{ij} + \varepsilon_{ij} \tag{7}$$

Where, “$\sum_{j=1}^{N} w_{ij} u_{ij}$ denotes the interaction effects between the disturbance terms of the different units, λ describes the spatial autocorrelation coefficient for the error lag”, the remaining symbols are the same as those expressed in Equation (6)

Finally, the Spatial Durbin Model (SDM) captures both endogenous and exogenous (explanatory) spatial interactions. The dependent variable is affected by the spatial lag term of the dependent variable and independent. Equation (8) represents the model:

$$y_{it} = \delta \sum_{j=1}^{N} w_{ij} y_{ij} + x_{it}\beta + \sum_{j=2}^{N} w_{ij} x_{jt}\theta + \mu_i + \xi_t + \varepsilon_{it} \tag{8}$$

Where, “$\sum_{j=2}^{N} w_{ij} x_{jt}$ denotes the exogenous interaction effects between the independent variables The term θ, as well as β, represent fixed and unknown parameters that must be estimated”.

The choice of model will be made taking into account whether the dependent or independent variables respond to spatial interaction effects.

3.2.3. Selection of spatial econometrics model

Regarding the existence of spatial autocorrelation in the dependent variable, the parameters estimate using Ordinary Least Squares (OLS) can lead to the loss of validity and inconsistency of the estimated parameters. However, Maximum Likelihood Estimation (MLE) provides with an unbiased estimate, which can effectively solve endogeneity problems.

Regarding the choice of the most appropriate spatial model, it is observed that “*the literature suggests two different approaches, the specific-to-general approach or the general-to-specific approach*” [50]. Elhorst [51] proposed a procedure incorporating both approaches. The first one estimates a non-spatial model to test both spatial lag and spatial error using the Lagrange Multiplier (LM) test (specific-to-general approach). The second one, in case the non-spatial model is rejected, the SDM is estimated to test whether it can be simplified to SLM or SEM (general-to-specific approach). Therefore, the parameters of the SDM are used to test the null hypotheses $H_0 : \theta = 0$ and $H_0 : \theta + \delta\beta = 0$. Commonly used test methods are the Likelihood Ratio (LR) test and the Wald test. Conversely, “*if the non-spatial model is rejected in favour of the SLM or the SEM, while the SDM is not, it is better to adopt the SDM*” [52].

3.3. Study area and data sources

A balanced panel sample of 43 countries in Europe and East Asia during the period 1990–2019 is used for this study (see appendix A). Table 1 shows the dependent variable, which is EE (*EE*) measured by an indicator of energy intensity (Gross Domestic Product (GDP) per unit of energy usage). In addition, the impact channels on a country's energy consumption, such as GDP per capita (*GDP*) and urbanization (*URB*).

On the other hand, renewable energies (*REN*) is taken from the Organization for Economic Co-operation and Development (OECD) (2021). Finally, both Financial Institutions Development (*FI*), financial market development (*FM*) and the export diversification index (*EDI*). Table 2 shows the descriptive analysis of the variables.

4. Empirical results

First, Moran's I and Geary's C are used to test the degree of spatial autocorrelation. “*A positive and statistically significant value of Moran's I indicates spatial clustering and a negative value of this index indicates spatial dispersion in the sample countries*” [56] (p.79). Meanwhile, a Geary's C value lower than 1 and significant indicates positive spatial autocorrelation, and a value between 1 and 2 indicates negative autocorrelation. EE data from the 43 study countries is used to calculate both statistics for each year from 1990 to 2019, and the average value for the period (see Table 3). Moran's I index is statistically significant at the 0.1% level. Likewise, the Geary's C statistic has significant values at 0.1% and less than 1, in other words, *EE* in the economies studied shows significant positive spatial autocorrelation. It should be taken into account that these global tests “can only be used to describe the average degree of global correlation” [57].

To further test for spatial autocorrelation, a Moran's I scatter plot is used for the years 1990, 1995, 2000, 2005, 2010 and 2015, which are reported in Fig. 1.

According to You & Lv [45], the statistical significance of Geary's C and Moran's I points to “the fact that traditional econometric models do not compensate for spatial autocorrelation, as they produce possibly biased estimators”. Therefore, Fig. 2 shows the spatial distribution of *EE*, where it is already observed that countries with a similar EE tend to group together, in other words, they form neighborhoods. It is important to understand that higher energy intensity levels (red-orange) have lower efficiency, while lower energy intensity levels (light blue-blue) are

Table 1
Variables.

Type	Name	Symbols	Definition	Source
Explained variable (Dependent variable)	Energy efficiency	*EE*	GDP per unit of energy usage	WDI [53]
Explanatory variables (Independent variable)	Gross Domestic Product	GDP	GDP per capita at constant 2015 prices	
	Urbanización	*URB*	Total urban population	
	Renewable energy	*REN*	contribution of renewables to total primary energy supply	OECD [54]
	Financial Institutions	*FI*	Financial Institution index	IMF [55]
	Financial Markets	*FM*	Financial Markets index	
	Export diversification	*EDI*	Export diversification Index	

Note: WDI= World Development Indicators. IMF = the International Monetary Fund. Data is provided by the World Bank [53] and the Financial Development Database and Export Diversification Database.

Table 2
Descriptive statistics.

Variables	lnEE	lnGDP	lnURB	lnREN	lnFI	lnFM	lnEDI
Mean	7.865	9.363	15.725	1.854	−0.781	−1.956	0.806
Media	7.917	9.361	15.566	1.950	−0.735	−1.258	0.729
Maximun	9.151	11.629	18.506	3.990	−0.007	−0.002	1.817
Minimun	5.898	5.785	12.641	−0.959	−3.048	−8.008	−0.043
Estandard deviation	0.576	1.886	1.273	1.126	0.511	1.807	0.341
Skewness	−0.534	−0.202	0.248	−0.280	−0.712	−1.241	0.876
Kurtosis	2.999	2.178	2.506	2.147	2.992	3.854	3.361
Jarque-Bera	61.234***	45.129***	26.407***	56.400***	108.989***	370.383***	172.179***
lnEE	1						
t-stat	–						
lnGDP	0.731***	1					
t-stat	38.505	–					
lnURB	0.113***	0.072	1				
t-stat	4.095	2.606	–				
lnREN	−0.015	0.301***	−0.267***	1			
t-stat	−0.563	11.333	−9.977	–			
lnFI	0.494***	0.812***	0.096*	0.203***	1		
t-stat	20.407	51.275	3.467	7.437	–		
lnFM	0.572***	0.766***	0.380***	0.109**	0.645***	1	
t-stat	25.035	42.841	14.763	3.262	30.314	–	
lnEDI	−0.295***	−0.424***	−0.117***	−0.204***	−0.477***	−0.355***	1
t-stat	−11.073	−16.834	−4.253	−7.497	−19.488	−13.641	–

Notes: **, and *** are the respectively significant levels at 5% and 1%. Values in the brackets are standard errors.

Table 3
Global Moran's I and Geary's tests.

Year	Moran's I	Geary's C	Year	Moran's I	Geary's C
1990	0.587***	0.382***	2005	0.524***	0.371***
1991	0.479***	0.458***	2006	0.541***	0.359***
1992	0.510***	0.418***	2007	0.534***	0.361***
1993	0.521***	0.403***	2008	0.558***	0.349***
1994	0.549***	0.355***	2009	0.571***	0.348***
1995	0.582***	0.333***	2010	0.581***	0.336***
1996	0.583***	0.325***	2011	0.565***	0.358***
1997	0.586***	0.326***	2012	0.574***	0.366***
1998	0.606***	0.313***	2013	0.597***	0.341***
1999	0.598***	0.330***	2014	0.586***	0.361***
2000	0.573***	0.352***	2015	0.608***	0.355***
2001	0.571***	0.350***	2016	0.615***	0.354***
2002	0.555***	0.357***	2017	0.619***	0.359***
2003	0.550***	0.358***	2018	0.621***	0.367***
2004	0.526***	0.370***	2019	0.619***	0.377***
			Average	0.544***	0.349***

Note: *** significance at the 0.1% level.

economies where there is a higher *EE*.

Finally, Fig. 3 shows the local Moran's I, local G_i of *EE* and Local Indicators of Spatial Association (LISA) clusters. In these it can be seen that Norway, Sweden, Finland, France, Germany, Netherlands and Belgium have a high local Moran's I (panel A), in addition to a high significance (panel B), whereas the rest of the economies show a significant local Moran's I at 10%. On the other hand, the local G_i of *EE* in panel C shows that all the economies have positive values, which implies that the economies are surrounded by relatively high values. Finally, in panel D of Fig. 3, LISA clusters are identified, which show the formation of neighborhoods between economies with a similar *EE* level. Consequently, it is feasible to apply spatial econometric models.

Continuing with the analyses, Table 4 shows the results of the estimates when adopting spatial panel data models (pooled OLS, spatial fixed effects, time-period fixed effects and spatial and time-period fixed effects) and the results of the LM tests to determine whether the spatial lag model or the spatial error model is more appropriate (Table 4). The results shown that the two proposed hypotheses are strongly rejected at the 1% significance level; (1) the null hypothesis that the dependent variable is not spatially lagged and (2) the null hypothesis that the error term is not spatially autocorrelated. However, when using robust tests, the hypothesis that the error term is not spatially autocorrelated can no longer be rejected at neither 5% nor 1% significance, for pooled and provided that time-period fixed effects or spatial and time-period fixed effects are included. Furthermore, it is important to control for spatial and/or time-period fixed effects. Therefore, a hypothesis (H_0) is made that spatial fixed effects are jointly insignificant, which is tested by performing the LR test. Taking into account the result obtained of 2653.30 with 43° of freedom [df], $p < 0.001$, this hypothesis should be rejected. Likewise, the result of 129.8, 30 df, $p < 0.001$, also indicates that the hypothesis that time-period fixed effects are jointly insignificant should be rejected. For this reason, applying the model with spatial and time-period fixed effects, also known as the two-way fixed effects model, is justified [58]. Therefore, the results point to a two-way spatial lag model specification.

Once the feasibility of the spatial models on the proposed relationship between the explained variable and the explanatory variables has been determined, it is important to look for the spatial relationship between them, therefore, from the Spatial Durbin Model (SDM) it is proposed to combine the weight matrix spatial analysis to establish the spillover relationships between the study variables, in other words, to present the advantages of measuring the impact between regions based on the SDM model. Table 5 shows the results of the Spatial Durbin model (first column shows the results of the estimation using the direct approach, the second column when the coefficients are subject to a bias correction). It is observed that the differences between both estimates are small for the independent variables. Likewise, the coefficients of the independent variables (*WX*) do not have significant variations, showing that the coefficients are sensitive to bias correction. Regarding whether the Durbin spatial model can simplify the spatial lag or spatial error model, the Wald and LR tests are performed. The results are reported at the bottom of Table 5, where both Wald and LR reject the null hypothesis, implying that both models should be rejected in favour of the SDM.

Regarding the third column of Table 5, the results of the estimates are shown considering random effects instead of a set of fixed effects. In addition, a Hausman [59] specification test was incorporated to test the random effects model against the fixed effects model. The test result (37.727, $p < 0.001$) indicates that the random effects model should be rejected. Baltagi [58] proposes as an alternative method to estimate the ''phi'' parameter in order to contrast the random effects model with the fixed effects model. ''phi'' parameter, measures the weight assigned to the cross-sectional component of the data and can take values between

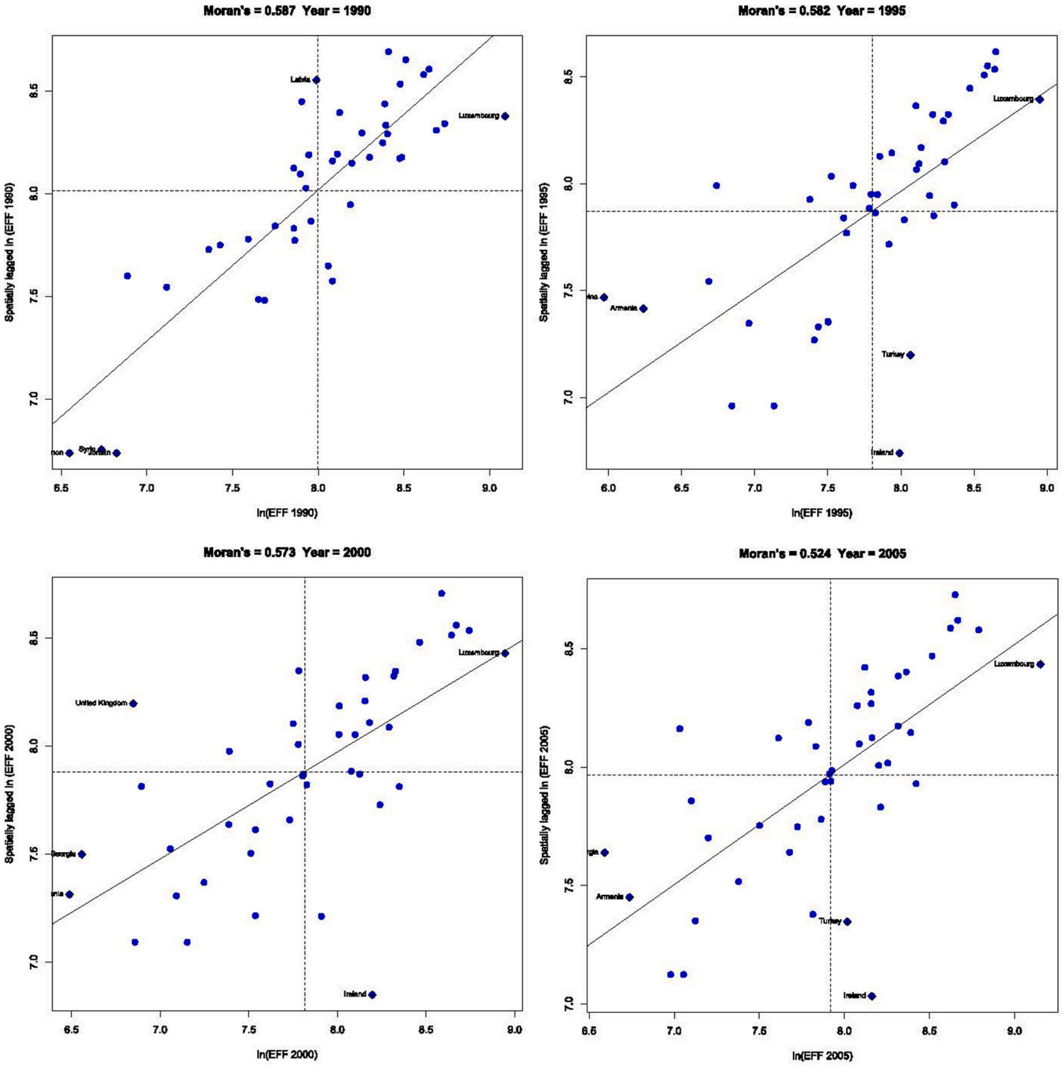

Fig. 1. Grafico de disperision del I Moran de la EE.

0 and 1. Therefore, if this parameter is equal to 0, the random effects model converges to its fixed effects counterpart; if it reaches 1, it converges to a model with no spatial-specific effect controls. The results show a statistically significant value of 0.027 at 0.01%, which, like the Hausman specification test, indicates that the fixed and random effects models are significantly different from each other [51]. Therefore, it is determined that the spatial model with spatial and time-period fixed effects with bias correction is the most efficient. In addition, the ρ is statistically significant at 1%, which shows that the growth of one unit in the *EE* of an economy can reduce the EE levels of a neighbouring country. This finding shows that the *EE* of the 43 European economies has an apparent spatial spillover effect. This result is supported by previous studies [60].

Regarding the Durbin spatial interaction results of the independent variables on *EE*, it is evident that there is a negative effect from the use of renewable energies $W * lnREN$ but not significant on *EE*, in other words, the efforts to implement and replace conventional forms of energy with sources such as: wind, solar, among others they have not reached sufficient levels in neighbouring economies to generate a favorable effect on the EE of the European economies under study. This result is contrary to that presented by Sztubecka et al. [61] and Han et al. [62], who argue that in China, the inevitable increase in industrial production has led to excessive energy consumption, which has motivated regions to adopt the use of alternative energies, generating a spillover effect on the rest of the provinces. On the other hand, the increase in economic growth W*lnGDP in neighbouring economies causes an increase in the energy intensity of the countries in the sample, that is, it reduces the EE. This would be linked to a non-sustainable growth process of some economies, which would imply that foreign production processes and management methods are not are helping to optimize resources. This result differs from that evidenced by Jiang et al. [63] and Wang et al. [64], suggesting that increased production promotes technological progress and where energy use would be optimized at sustainable levels, like Bataille & Melton [16] and Sener & Karakas [19]. However, growth alone does not stimulate *EE*, which is not enough to guarantee environmental improvements [65].

Along this same line of analysis, urbanization $W * lnURB$ has a negative impact on the EE of the economies, in other words, an increase in the urbanization of neighbouring economies decreases the energy intensity of the economies under study, therefore, it increases the EE. Likewise, internal urbanization processes of economies would be related to a shift from the consumption of more traditional energies to the consumption of cleaner sources. This result is similar to those presented by Kiziltan [66] in Turkey and Yang et al. [67] in China, who argue that as urbanization increases, electricity use become more efficient. On the other hand, Wang [47], Lv et al. [68] and Sun et al. [69] find a negative

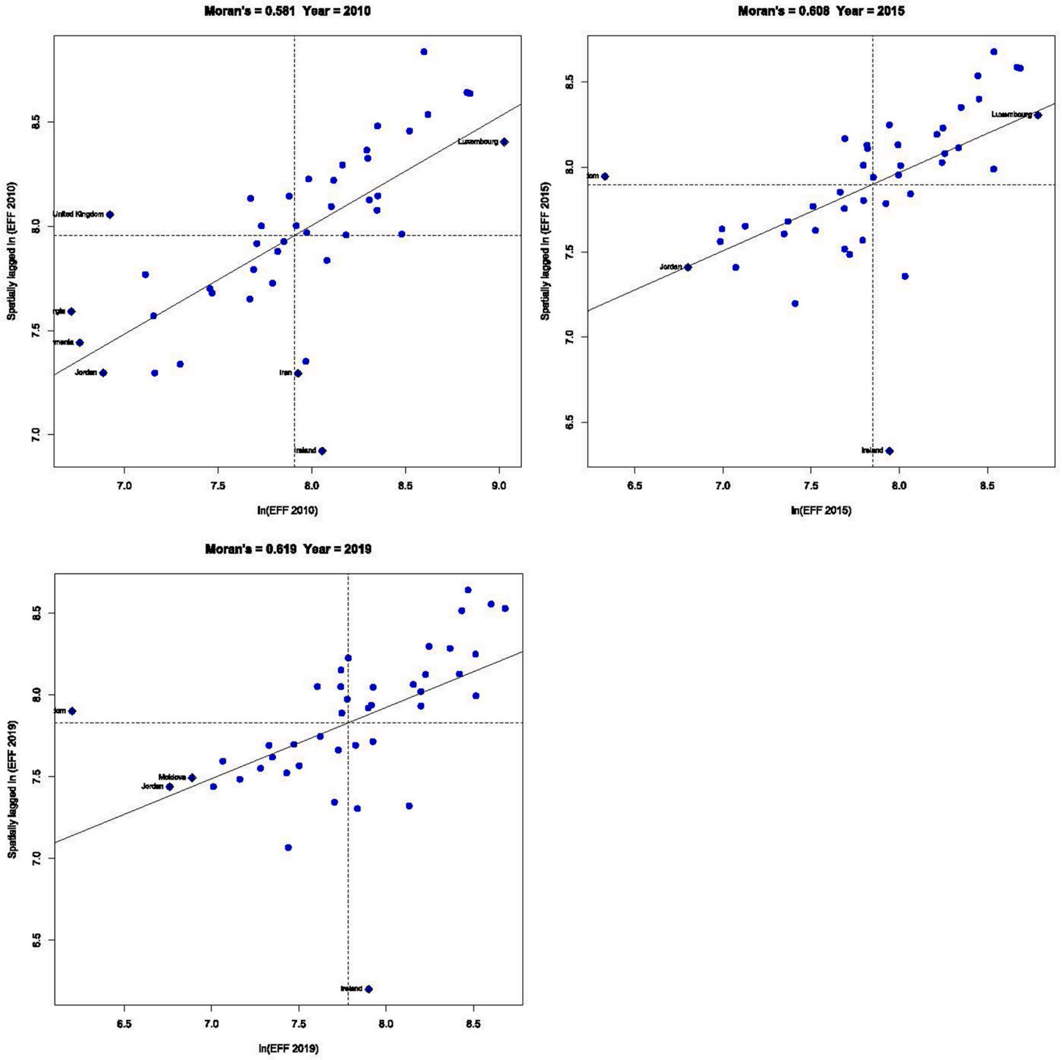

Fig. 1. (*continued*).

relationship between urbanization and EE. In addition, it should be considered that some regions of Europe are facing a persistent decline in population [70], which would imply a decline in energy demand.

On the other hand, financial development considered from both the institutional and market perspective generates heterogeneous effects on the EE of economies where only the spatial market component of financial development has a positive and significant impact on EE which means that an increase in Financial Markets index in neighbouring economies increases the EE in the sample countries. This would be related to the persistent increase in stock market activities and development, which would imply channeling of financial resources that would create a high demand for energy in the industry. This result would be in line with Mi et al. [71] and Li et al. [72], who consider that tertiary activities, such as finance, are more flexible and lead to a higher level of market demand, which results in a greater number of activities and, in turn, greater energy consumption. However, Hao et al. [73] consider that a higher technical level of the tertiary industry improves the efficiency of use of various production factors. Finally, an increase in the index of diversification of exports from neighbouring economies generates a decrease in the EE of the economies under study. This result is consistent with Afonso et al. [40] and Wei et al. [39] regarding the demand that certain sectors exert on total energy consumption.

Based on the Spatial Durbin model, this investigation additionally calculates the direct and indirect effects of REN, GDP, URB, FI, FM and EDI on the EE of European economies. Table 6 shows three effects of the SDM model with two-way correction. The results can be classified into two categories [62,74].

In the first category are the variables *lnREN* and *lnURB*, which have a negative and significant indirect effect on EE. The first one is important, since the incorporation of renewable energies in an economy promotes a spatial spillover effect on the *EE* of neighbouring economies. However, the direct effect is greater than the indirect effect, which would result in a more significant return effect. Hence, the average effect on neighbouring economies shown in Table 5 was found to be insignificant. These spillover effects imply that the use of renewable energies gives rise to an increase in *EE* and becomes a primary driver for the increase in energy efficiency. This would be supported by other studies that find similar effects [6,7]. In addition, the adoption of cleaner fuels for domestic use and the reduction of environmental degradation could be an effect that boosts the rest of the economies [21].

Likewise, the spillover effect of *lnURB* is negative and significant, 0.397 to be precise, that is, spat6,ially, urbanization generates a decrease in energy consumption, which would imply an improvement in *EE*. However, the direct or return effect shows that urbanization increases energy intensity levels, significantly reducing the *EE* of the economies themselves. Therefore, technological advantages and economies of scale outweigh the negative effects related to the demand that the growth of the urban sector involves [75].

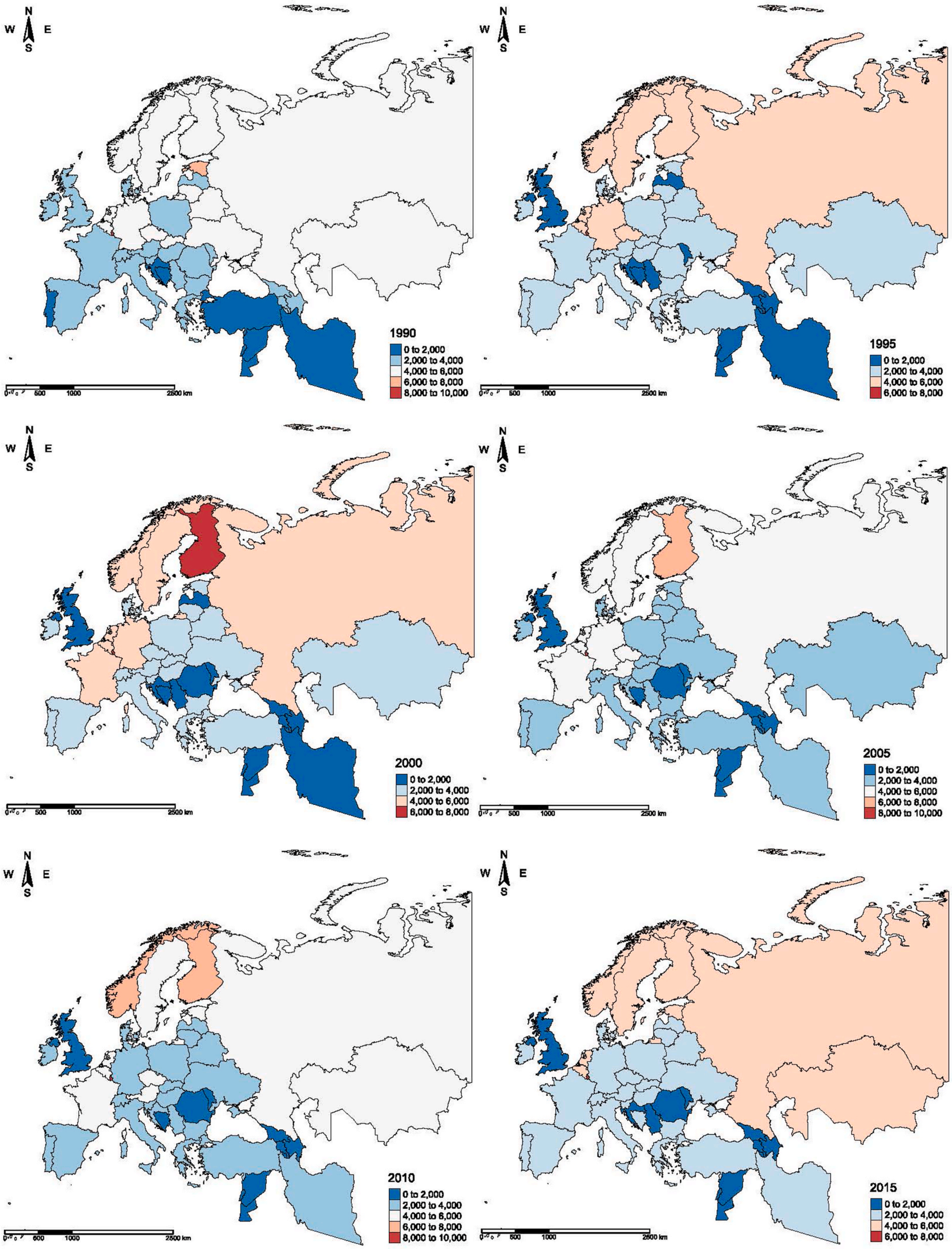

Fig. 2. Spatial distribution of Energy efficiency. Notes: the class breaks correspond to quantiles of the distribution of the variable for each year.

The second category presents variables that are associated with a positive effect, that is, they increase energy intensity, which directly leads to a decrease in the *EE* of European economies. In this regard, *lnGDP* generates a positive impact on *EE*, in both the direct and indirect effects. This would imply that the growth levels of European economies promote a decrease in efficiency, as a result of an increase in the energy intensity of neighbouring economies. On the other hand, it is evident that the components of financial development have heterogeneous effects. First, institutional financial development (*lnFI*) promotes an improvement in efficiency within the same economy through the direct effect. Second, the development of financial markets (*lnFM*) generates a spillover effect on the *EE* of neighbouring economies. Therefore, the

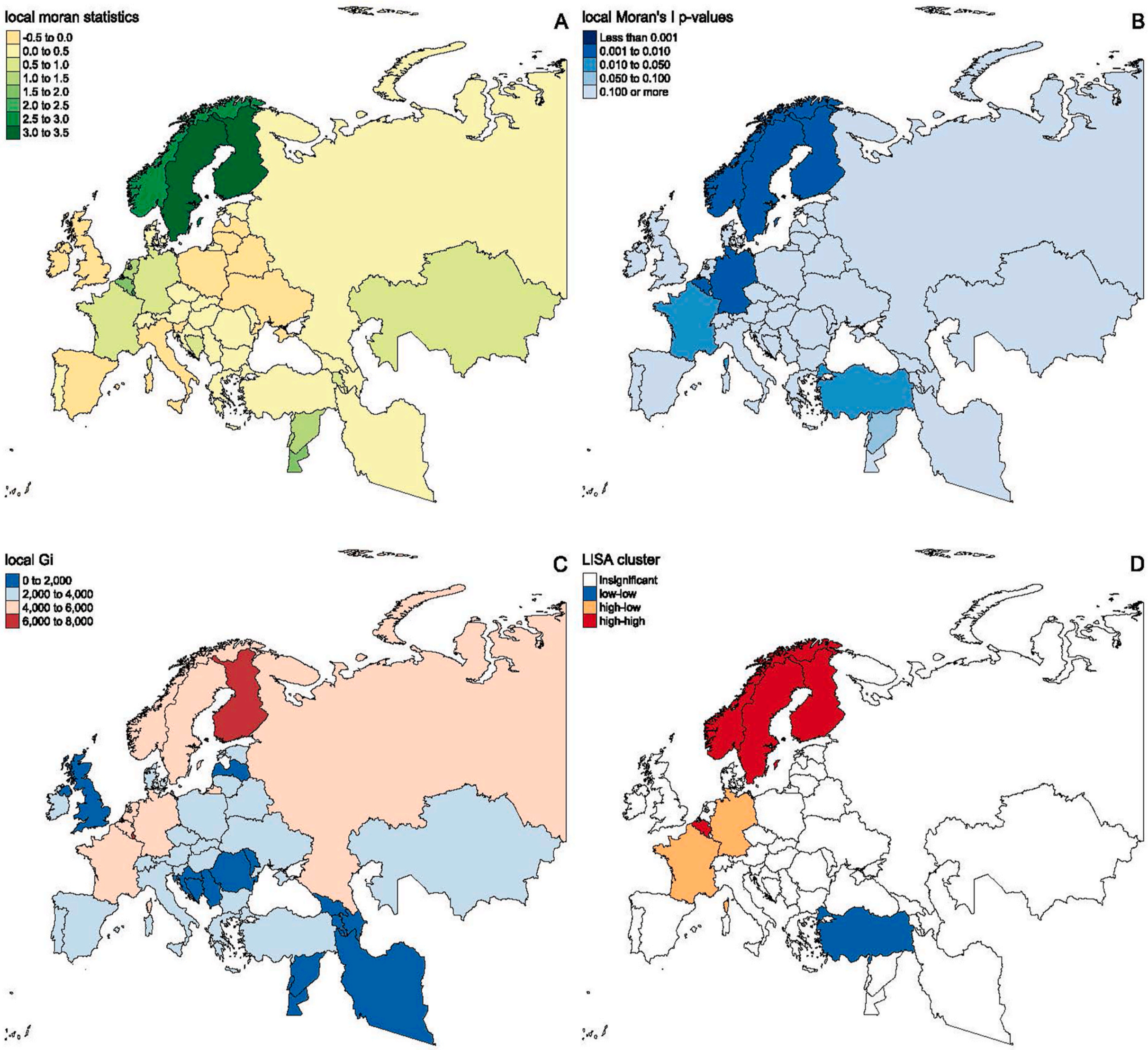

Fig. 3. Local Moran's I, Local G_i and LISA of Energy efficiency from 1990 to 2018.

evidence presented by Yao et al. [10] and Atta Mills et al. [11] is indisputable, not all economies worldwide have sophisticated levels of financial development, which implies that the pressure on them generates an increase in energy demand.

Finally, export diversification increases domestic *EE* and decreases the efficiency of neighbouring economies. This is related to the direct-positive and indirect-negative effect, respectively. In general, as the results show, it is essential to apply more specific strategies linked to the improvement in energy production, based on a more intelligent growth and with more sophisticated processes, which allow for a decrease in current energy demand.

4.1. Robustness checks

Depending on the choice of the spatial weight matrix, the estimated results can be affected, so it is important to calculate the SDM model with different matrices to ensure the robustness of the results. The K nearest neighbour spatial weights matrix is considered and two additional matrices are established using K-7 and K-8 distances, that is, the countries share 7 and 8 neighbours, respectively. The estimated results for K-7 nearest Distance and K-8 nearest Distance can be seen in Table 6, two additional spatial weight matrices, the results being very similar. Therefore, it is observed that direct, indirect and total estimates are very similar regardless of the spatial weighting matrix used.

5. Conclusions

Economies worldwide face significant challenges in coping with an increase in energy consumption and environmental sustainability. The vast majority of European countries have proposed to be climate neutral with respect to net CO2 emissions by the year 2050. On the other hand, there are actions to reduce energy consumption through EE and the use of renewable energies that have been incorporated in the SDGs. EE is a cost-effective way to achieve a reduction in energy consumption and carbon emissions, which would imply improving environmental sustainability. Therefore, EE is established as a sustainable development goal. Most of the previous investigations focus on study the average relationship between economic growth, energy consumption and financial development. Their analyses do not consider the spatial behaviour of the variables and their country samples are very small. Therefore, this study focuses on the relationship between EE, the use of renewable energies and financial development, in addition to considering the theoretical components of the STIRPAT model. The study sample includes 43 European countries for the period 1990–2019, where the majority of the economies have established policies with the aim of promoting the aimed at obtaining sustainable economic development

Table 4
Results of the spatial panel data models.

	Pooled OLS	Spatial fixed effects	Time-period fixed effects	Spatial and time-period fixed effects
lnREN	−0.148***	−0.249***	−0.141***	−0.202***
	(-15.564)	(-30.222)	(-13.895)	(-20.758)
lnGDP	0.552***	0.312***	0.551***	0.371***
	(30.337)	(17.121)	(30.249)	(18.903)
lnURB	0.0003	0.211***	0.002	0.374***
	(-0.033)	(6.388)	(0.219)	(9.297)
lnFM	−0.015	0.058***	−0.014	0.083***
	(-1.527)	(6.423)	(-1.477)	(9.140)
lnFI	−0.432***	−0.094***	−0.425***	−0.062**
	(-12.665)	(-4.360)	(-11.457)	(-2.754)
lnEDI	−0.118***	0.022	−0.100**	0.033
	(-3.622)	(0.836)	(-2.819)	(1.304)
Intercert	2.705***			
	(9.809)			
R^2	0.642	0.471	0.646	0.485
adj.R-sq	0.640	0.469	0.644	0.483
σ^2	0.119	0.017	0.117	0.015
Durbin–Watson	1.844	1.621	1.186	1.831
Log-likelihood	−456.35	797.31	−444.42	876.17
LM spatial lag	589.49***	58.56***	575.11***	23.68***
LM spatial error	500.25***	56.78***	472.99***	15.30***
Robust LM spatial lag	103.13***	6.07**	110.89***	8.41**
Robust LM spatial error	13.89***	4.28*	8.77***	0.04

Note: *** denote a significance of 0.1%, **1%, and * 5%.

Table 5
The spatial panel model.

	Spatial and time-period fixed effects	Spatial and time-period fixed effects bias-corrected	Random spatial effects, fixed time-period effects
ρ	0.095**	0.129***	0.084**
	(2.946)	(4.030)	(2.599)
lnREN	−0.186***	−0.185***	−0.190***
	(-17.881)	(-17.360)	(-17.973)
lnGDP	0.299***	0.298***	0.303***
	(14.719)	(14.249)	(14.755)
lnURB	0.636***	0.640***	0.502***
	(14.204)	(13.903)	(12.179)
lnFM	0.072***	0.072***	0.067***
	(8.342)	(8.072)	(7.698)
lnFI	−0.117***	−0.116***	−0.124***
	(-5.184)	(-5.013)	(-5.410)
lnEDI	−0.073**	−0.076**	−0.061*
	(-2.938)	(-2.966)	(-2.413)
W*lnREN	−0.021	−0.014	−0.025
	(-1.289)	(-0.865)	(-1.551)
W*lnGDP	0.212***	0.197***	0.181***
	(5.515)	(5.030)	(4.765)
W*lnURB	−0.426***	−0.440***	−0.312***
	(-6.738)	(-6.791)	(-5.258)
W*lnFM	0.050***	0.047**	0.060***
	(2.899)	(2.630)	(3.475)
W*lnFI	−0.034	−0.031	−0.032
	(-0.892)	(-0.792)	(-0.824)
W*lnEDI	0.328***	0.325***	0.315***
	(7.989)	(7.720)	(7.583)
phi			0.024***
			(6.559)
σ^2	0.013	0.014	0.013
(Pseudo) R^2	0.961	0.961	0.959
(Pseudo) Corrected R^2	0.556	0.556	0.261
Log-likelihood	975.73	975.73	789.48
Wald test spatial lag	186.19***	174.56***	150.83***
LR test spatial lag	170.19***	170.19***	120.34***
Wald test spatial error	185.34***	172.88***	155.56***
LR test spatial error	177.87***	177.87***	139.32***

Note: *** denote a significance of 0.1%, ** 1%, and * 5%.

and financial by incorporating cleaner technologies such as renewable energies, which would allow for a transition of the population and industry to more efficient production processes. Therefore, this research follows an original and novel approach, which incorporates the spatial component by using the Spatial Durbin Model (SDM) on a sample of Eastern European economies that have been highly dependent on Western European economies for energy supply. As a result, this research fills the gap in the previous literature, which normally explores the link between EE and economic growth.

Two stages were followed in the investigation. In the first, the spatial autocorrelation of EE measured by energy intensity was established. Moran's I and Geary's C statistics confirmed the presence of positive spatial autocorrelation. However, the state of EE in Europe differs between countries. Economies such as Finland, Sweden, Norway, Estonia, Kazakhstan, the Netherlands, Belgium and Russia showed high levels of energy consumption per capita, that is, lower EE. On the other hand, economies such as the United Kingdom, Italy, Spain and France have higher levels of efficiency in the study region.

In the second stage, the relationship between EE, renewable energy use and financial development was investigated. The results show that the use of renewable energies generates an indirect or spatial spillover effect on neighbouring countries, as well as a direct or return effect on the economy itself. On the other hand, the components of financial development differ in their effect on EE. Nevertheless, the development of stock markets increases the demand for energy supply, a result that is confirmed by the direct and indirect effects of the SDM model, while the institutional component of financial development shows that it generates a return effect that improves EE levels. Finally, the theoretical components of the STIRPAT model show that both economic growth and trade openness, the latter measured by export diversification, exert detrimental effects on efficiency levels, whereas urbanization promotes a statistically significant EE on neighbouring economies. These results do not differ from the direct and indirect effects estimated from the SDM model.

Therefore, it is necessary to implement policies to accelerate the transition to renewable energy use and to promote sustainable financial development. There is also a clear need to implement policies that promote energy efficiency, introduce EE technologies, improve EE in certain industries and diversify energy sources, especially in countries with a high dependence on more traditional energy supply. In addition, the development of sustainable financial institutions and markets is necessary, which integrate objectives linked to the sustainable development goals. Moreover, European economies should focus their policies on achieving a balance in the relationship between EE, the use of renewable energies and sustainable financial development.

Finally, the lack of data for all European countries, especially those related to EE is the main limitation of this research work. Given that European countries show progress in terms of efficiency in relation to the rest of the regions, future research could identify other spatial factors that promote or limit EE. Additional analyses can be made by including the rest of the world's regions and observing the global spatial behaviour of the factors.

Credit author statement

All authors listed have made a substantial, direct and intellectual contribution to the work and approved it for publication. B.Q., M.d.l.C. d.R.-R., J. Á-G, and F.V.-B.: conceptualization, investigation,

Table 6
Direct and Indirect Effects. Queen matrix and other.

Variables	Queen matrix			K-7 nearest Distance			K-8 nearest Distance		
	D	I	Total	D	I	Total	D	I	Total
lnREN	−0.187***	−0.043**	−0.229***	−0.199***	0.009	−0.190***	−0.205***	0.005	−0.201***
	(-17.873)	(-2.621)	(-13.753)	(-18.443)	(0.366)	(-8.132)	(-19.762)	(0.182)	(-8.009)
lnGDP	0.307***	0.262***	0.570***	0.379***	−0.057	0.323***	0.359***	−0.309***	0.050
	(14.738)	(6.406)	(13.368)	(18.703)	(-0.932)	(4.758)	(18.466)	(-4.579)	(0.684)
lnURB	0.626***	−0.397***	0.228**	0.510***	−0.451***	0.059	0.508***	−0.487***	0.021
	(13.278)	(-5.814)	(2.983)	(11.954)	(-4.600)	(0.580)	(11.743)	(-4.873)	(0.204)
lnFM	0.073***	0.061**	0.135***	0.088***	−0.005	0.083**	0.094***	−0.043	0.052
	(8.241)	(3.276)	(6.382)	(9.564)	(-0.224)	(3.086)	(10.380)	(-1.583)	(1.747)
lnFI	−0.117***	−0.051	−0.168**	−0.043	−0.029	−0.072	−0.048*	0.226***	0.177**
	(-5.062)	(-1.185)	(-3.577)	(-1.773)	(-0.547)	(-1.233)	(-2.025)	(3.773)	(2.807)
lnEDI	−0.063*	0.349***	0.286***	−0.018	0.432***	0.414***	0.008	0.581***	0.590***
	(-2.498)	(7.688)	(5.625)	(-0.696)	(7.174)	(6.467)	(0.316)	(8.143)	(7.942)

Note: *** denote a significance of 0.1%, ** 1% and * 5%. D = direct, I = indirect.

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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.

Appendix

Table 1A
Study countries

Countries			
Azerbaijan	Finland	Lebanon	Russian Federation
Armenia	France	Latvia	Slovenia
Austria	Georgia	Lithuania	Spain
Belgium	Germany	Slovak Republic	Serbia
Bosnia and Herzegovina	Greece	Luxembourg	Sweden
Belarus	Croatia	Moldova	Syrian Arab Republic
Bulgaria	Hungary	Netherlands	Switzerland
Denmark	Iran, Islamic Rep.	Norway	Turkey
Ireland	Italy	Poland	United Kingdom
Estonia	Jordan	Portugal	Ukraine
Czech Republic	Kazakhstan	Romania	

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