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Women's political empowerment and electricity affordability: A spatial analysis

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ABSTRACT

This study examines the role of women's political empowerment on energy costs in the context of 22 EU economies. We estimate Spatial Durbin Models (SDM) and Spatial Autoregressive Models (SAR) to evaluate the direct, indirect and cross-sectional spillover. The empirical results divulge that women's political empowerment would be an effective and significant mechanism to reduce energy costs in EU economies. In addition, efficient resources allocation and women-led governance serves as a key channel for reducing energy costs. In contrast, environmental-related technologies progress, renewable energy and economic growth upward pressures on costs. This finding enlightens the importance of gender-sensitive policies into energy pricing planning affordability. Policymakers should consider fostering women's participation in political decision-making as part of broader efforts to improve energy sector performance and ensure inclusive, sustainable access to affordable energy.

1. Introduction

Since oil crisis of 1973 and 1979, energy sector has given priority because of its critical dimension associated with environmental sustainability, social equity and economic development. According to Bekhet & Yusop (2009) and Atil et al. (2020), technological innovation, renewable energy and economic growth are the major dimension of energy pricing dynamics. However, gender-sensitivity response particularly women's political empowerment shaping the distribution of energy pricing is scare in the context of developed economies and emerging market developing economies. According to Dollar et al. (2001) and Chattopadhyay & Duflo (2004), women's political empowerment and their involvement has been indicated to improve governance through control of corruption, effective public expenses, and governance quality. These improvements and efficacy are particularly applicable in energy sector reforms where effective allocation of resources can be accountable with lower energy price charges and quality service. Despite these potential links, empirical evidence connecting women's political empowerment to energy affordability remains limited, particularly in a spatially explicit context.

At the same vein, women political empowerment in political decision marking has been linked with transparency, inclusive public utilities and accountability in policy design (Dollar et al., 2001; Chattopadhyay and Duflo, 2004). In this context of energy sector, it influences electricity affordability via better procurement practice, enhance regulatory utilities and subsidy allocation. In addition, women participation in political decision making often emphasis household welfare and social services which may create reliable and affordable access in electricity market. These mechanisms not only play a significant role in shaping energy sector reforms by reinforcing the importance of examining the gender–energy nexus within broader discussions of energy affordability and sustainable development.

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This study contributes into three folds. First, it investigates the role of women's political empowerment on energy costs in the context of EU economies. Second, we use Spatial Durbin Models (SDM) and Spatial Autoregressive Models (SAR) to quantify the direct effects, indirect and cross-sectional spillover of women's political representation on energy prices. This approach may allow to solve the complex interdependencies that characterize energy markets and policy environments. Third, it also explains the different mechanism and directions through which energy costs are affected empirically and drive relevant policies. Fourth, empirical finding provides that women's political empowerment is highly associated with the reduction of energy costs. In addition, environmental related technologies, renewable energy adoption and economic growth strategies push up the energy costs significantly. These results suggest that policies fostering women's participation in political decision-making can deliver broad co-benefits beyond improvements in equity and representation. Moreover, the analysis confirms that technological progress, renewable energy adoption and economic growth strategies, while essential for modernization, contribute to upward cost pressures that must be managed through complementary strategies.

The remainder of the paper is structured as follows. Section 2 reviews the relevant literature on energy costs, spatial dependence, and gender-responsive governance. Section 3 describes the data sources and econometric methodology. Section 4 presents and discusses the estimation results. Section 5 concludes with policy implications and directions for future research.

2. Literature review

2.1. *Determinants of energy costs and price*

Energy sector plays a vital role in sustaining economic development, household welfare, and industrial competitiveness. A couple of studies use economic growth, technological innovation and renewable energy are the main determinants of energy costs (Bekhet and Yusop, 2009; Newell et al., 2019; Atil et al., 2020). According to IEA (2020), technology and renewable energy are the crucial factor in the long-run environmental sustainability and energy security for developed and developing economies because of transitional costs, grid modernization and capital-intensive investments. Sadorsky (2000) and Blázquez et al. (2017) find that energy price and economic growth are associated by demand-pull dynamic where better economic growth stimulates standard of living of larger mases and highlight the upward slope of energy usage, and pressure on supply constraints and finally exerting inflationary pressure on electricity costs. Borenstein and Davis (2016) find that price regulation and subsidies policies produce distributional effect. Carley and Konisky (2020) examine that energy transition and decarbonization target balance with the risk of energy poverty. Del Río and Mir-Artigues (2014) show if renewable energy is not structured carefully, it may lead to accelerate energy costs. According to (Sovacool (2012) and World Bank (2018), institutional capacity and governance determine the efficacy and performance of energy sector through infrastructure planning, regulatory enforcement and service reliability to reduce the energy costs. Estache & Goicoechea (2005) highlight that weak accountability and corruption mechanism persist cost in energy infrastructure while Bloom et al. (2010) and Buntaine and Parks (2013) conclude that strong checks and balances of institution efficiently gain electricity distribution.

2.2. *Women's political empowerment and energy costs*

Despite these insights, studies examining the determinant of energy costs, even governance–energy cost nexus often overlook the specific influence of gender representation within political institutions. This omission is notable given evidence that women's political participation can improve budgetary transparency, reduce rent-seeking behaviour, and heighten responsiveness to public service delivery (Chattopadhyay and Duflo, 2004; Dollar et al., 2001). Moreover, Hoogendoorn et al. (2013) and Post & Byron (2015) highlight that greater diversity in decision-making bodies leads to better oversight and more innovative solutions to complex policy challenges. Dollar et al. (2001) concludes that women's participation in political decision-making has been associated with lower levels of corruption while Chattopadhyay & Duflo (2004) find that transparency and effective resources allocation can reduce costs. Moreover, Terjesen et al. (2009) and Post & Byron (2015) illustrate that organizational performance matter for lowering energy. Complementing this perspective, the United Nations (2020) underscores that women's leadership contributes to more equitable, transparent, and cost-effective delivery of energy services. Miller (2008) shows that female policymakers are more likely to invest in public goods, including energy infrastructure that benefits marginalized populations. These insights collectively suggest that gender-responsive governance may play a critical role in reducing electricity costs and mitigating spatial disparities in affordability.

Despite the recognized benefits of women's political empowerment for governance broadly, empirical studies directly linking gender representation to energy affordability remain limited. Most research focuses on access and reliability rather than price effects (IEA, 2020). Moreover, the spatial dimension—capturing how women's political empowerment influences EU economies energy costs—has been unnoticed. Given the interconnected nature of energy markets and policy diffusion, understanding these spatial spillovers is essential for designing effective and inclusive energy strategies. This study addresses this gap by examining how women's political empowerment affects regional energy costs and their spatial distribution. By applying Spatial Durbin and Spatial Autoregressive Models, we provide novel insights into both direct impacts within regions and indirect spillover effects across borders. In doing so, this research contributes to the emerging literature at the intersection of gender-responsive governance and energy economics and offers evidence to inform more inclusive and effective policy design.

3. Theoretical understanding between Women's political empowerment and electricity cost

Theoretical perspectives from institutional economics, spatial development theory, and gender studies suggest that women's political empowerment may play a distinctive role in influencing both local energy costs and cross-regional spillover effects. From an institutional economics perspective, governance quality critically affects how efficiently energy resources are allocated and how effectively infrastructure investments are managed (North, 1990; Estache and Goicoechea, 2005). Women's political participation has been associated with enhanced transparency, reduced corruption, and improved accountability (Dollar et al., 2001; Chattopadhyay and Duflo, 2004). These attributes can lead to better-targeted subsidies, more reliable pricing regulations, and greater enforcement of performance standards, all of which lower electricity costs locally. Female representation is highly linked with higher transparency, procurement efficiency, or anti-corruption in the energy sector through different mechanisms. First, improved governance strategies can minimize rent-seeking and procurement inefficiencies via lower operational costs for utilities and improves pricing efficiency. In electricity markets—where infrastructure procurement, fuel purchasing, and tariff setting involve large public expenditures—greater transparency can directly translate into lower consumer prices. Secondly, Female policy makers may emphasis policies that enhance subsidies, reliable infrastructure investment, and electricity provision in as efficient way. Finally, it may also strengthen institutional accountability via monitoring of public utilities that reduce resources misallocation and improve distribution system efficacy ultimately contributing to lower electricity costs. Further, it also encourages decentralized energy technologies and renewable energy adoption which can reduce price volatility, long-run energy generation costs. Female leadership has often been associated with stronger support for sustainable development and environmental policies.

The spatial dimension of electricity costs emerges because energy markets are inherently networked. Electricity production and distribution infrastructure often serve multiple regions through interconnected grids, creating spatial dependencies in prices (LeSage and Pace, 2009). Policy reforms or governance improvements in one jurisdiction can therefore generate spillover effects by influencing wholesale market transactions, cross-border flows, and competitive pressures on neighbouring regions. Integrating a gender-responsive governance lens into this spatial framework implies that regions with higher levels of women's political empowerment are likely to experience improvements in the quality and efficiency of regulatory oversight. As these improvements take hold, they can exert downward pressure on electricity costs that radiate outward via three main channels: (1) infrastructure spillover, (2) policy diffusion, and (3) market integration.

Fig. 1 illustrates the conceptual framework linking women's political empowerment to electricity cost reductions through direct local improvements and indirect regional spillover mechanisms. At the top of the diagram, Women's Political Empowerment, operationalized as higher female political representation in local and regional governance structures, is posited to act as a central institutional driver of governance quality via transparency, efficacy and accountability. The framework distinguishes between two primary pathways: First, on the left side, increased women's participation is theorized to strengthen efficient energy policies particularly by enhancing procurement, subsidy targets and planning. This, in turn, contributes to Local Electricity Cost Reduction, achieved through mechanisms such as more effective subsidy targeting and improved procurement practices. These localized improvements directly alleviate affordability constraints and reduce inefficiencies in electricity service provision. Second, on the right side, women's political empowerment is expected to improve regional energy regulation via monitoring utilities and tariff transparency across administrative boundaries. Through this channel, Spillover Mechanisms emerge, including.

1. **Infrastructure Spillovers:** Transparent procurement and better governance reduce infrastructure costs. Because neighbouring regions often purchase power through shared grids or bilateral agreements, these efficiency gains can indirectly lower their input costs.
2. **Policy Diffusion:** Regions with more inclusive governance structures may develop innovative pricing policies or subsidy schemes that become benchmarks for neighbouring jurisdictions, fostering regulatory convergence and competitive pricing dynamics.
3. **Market Integration:** Improved governance increases investor confidence and attracts private participation in electricity generation. As capacity expands in one area, surplus generation can be transmitted to adjacent regions, easing supply constraints and stabilizing prices more broadly.

These spillovers collectively lower electricity costs beyond the originating jurisdiction. At the bottom of the diagram, the convergence of both pathways leads to **Lower Electricity Costs in Neighbouring Regions**, conceptualized here as **spatial spillovers**. This component emphasizes that improvements in one region can propagate across space, reinforcing affordability and sustainability objectives in connected electricity markets. This framework provides a theoretical justification for the empirical estimation strategy adopted in this study, which employs spatial econometric models to quantify both **direct effects** and **indirect spillovers** arising from gender-responsive governance reforms.

4. Methodology

4.1. Empirical strategy and rationale

Building on the conceptual framework presented in Fig. 1, this study applies spatial econometric models to quantify the relationship between women's political empowerment and regional electricity costs. The framework posits that gender-responsive governance reduces electricity costs via two channels: (i) direct local improvements in governance efficiency and procurement practices, and (ii) indirect spillover effects transmitted through interconnected energy infrastructure, policy diffusion, and market integration. To rigorously capture these channels, we estimate two complementary specifications: the **Spatial Durbin Model (SDM)** and the **Spatial Autoregressive Model (SAR)**. The SDM allows for spatial lags of both the dependent variable and the explanatory variables, providing a flexible structure that accommodates spillovers in both outcomes and covariates. The SAR model, in contrast, restricts spatial dependence to the dependent variable alone and is used as a robustness check to isolate spillovers attributable solely to interregional price dependencies.

Formally, the SDM is expressed as follows:

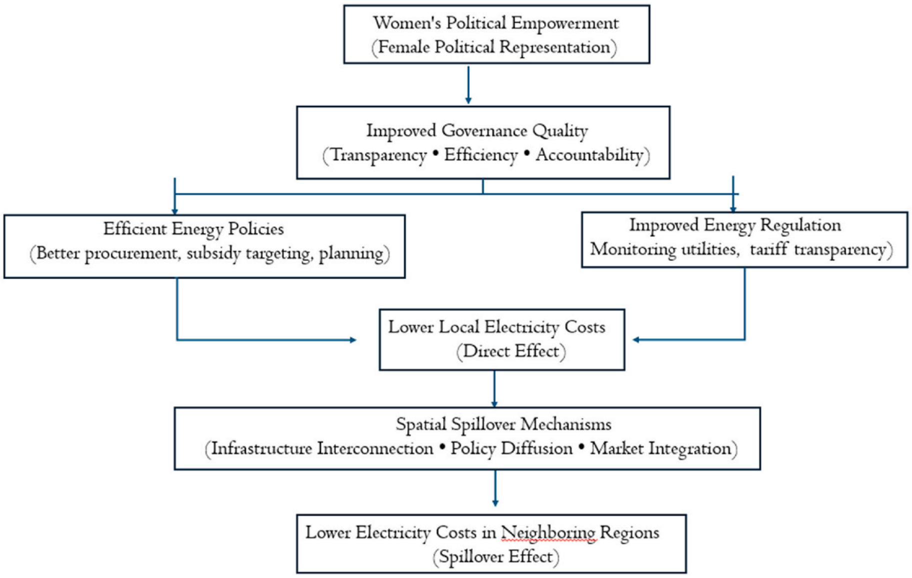

Fig. 1. Conceptual framework. Source: Authors representation.

$$Ln\ ENG\_CST_i = \rho\sum_{j}\delta_{ij}LnENG\_CST_j + X_i\beta + \sum_{j}\delta_{ij}X_j\varnothing + \varphi_{it} \tag{1}$$

where $Ln\ ENG\_CST_i$ denotes the log of electricity costs in region I, ρ captures the spatial autoregressive coefficient (the spillover in costs), δ_{ij} are elements of the spatial weight matrix reflecting contiguity or inverse distance between regions i and j, X_i is a vector of explanatory variables, including women's political empowerment ($LnGen_{\ i}$), technological progress ($LnTech_i$), renewable energy deployment ($LnRen_i$), and economic growth ($LnGDP_i$), $\varnothing$ captures the spatial lag coefficients of the regressors, φ_{it} is the idiosyncratic error term.

This specification allows us to decompose the total marginal effects of women's political empowerment into: (1) **Direct Effects**: the impact within the focal region (the left pathway in Fig. 1), (2) **Indirect Effects**: the spillovers to neighbouring regions (the right pathway in Fig. 1) and (3) **Total Effects**: the sum of both channels. The SAR model is specified more parsimoniously:

$$Ln\ ENG\_CST_i = \rho\sum_{j}\delta_{ij}LnENG\_CST_j + X_i\beta + \varphi_{it} \tag{2}$$

Initially, the application of spatial panel regressions requires constructing the spatial weight matrix. This matrix is an exogenous parameter that calculates the degree of spatial dependency among the state *i* and *j* within the study sample. In this context, this study follows the Queen contiguity method to create a weight matrix, which assigns a weight of 1 for spatial units that share either a common boundary or vertex, while all other non-adjacent units receive a weight of 0. In Equation (3), W is an n × n spatial weights matrix representing the adjacency structure among spatial units.

$$W_{ij} = \begin{cases} 1, \text{countries i and j are neighboring countries} \\ 0, \text{countries i and j are not neighboring countries} \end{cases} \tag{3}$$

Empirically, Queen contiguity weights approach can capable of identifying a larger set of neighbouring units, thereby capturing broader and more realistic spatial interactions (Guo et al., 2025; Hossain et al., 2025). Therefore, this contiguity matrix is preferable in spatial analysis spatial spillovers, as it reduces the likelihood of isolated regions and yields more robust spatial models, particularly when the underlying processes diffuse through both shared borders and points of contact (Anselin, 1988).

4.2. Data and variables

We started the empirical analysis by examining some important dispersion and central tendency measures for the underlying variables. Our empirical analysis covers the period from 1990 to 2019 and includes 22 European Union member states, selected based on data availability and reliability. The dependent variable is the regional log of electricity costs[1] ($Ln\ ENG\_CST_i$). The key independent variable of interest is an index of women's political empowerment[2] (lnGen − 1), proxied by the share of women holding elected office in regional legislative bodies. Control variables include: $Ln\ Tech_i$ is the development of environment-related technologies, % all technologies, $LnRen_i$ is renewable energy supply, % total energy supply, and $Ln\ GDP_i$ is the real GDP per capita (US $), 2015. Women's political empowerment includes the dimensions of civil liberties, civil society participation, and political participation (Sundström et al., 2017). The renewable energy ratio includes hydro, solar, wind, biofuels, and other renewable sources (OECD, 2024). The environmental technologies indicator includes energy efficiency, waste management, pollution control, and clean transportation technologies. Electricity costs are measured in real terms, adjusted for inflation, allowing comparisons between periods and regions (Liddle, 2022). The data are balanced with no missing observation for the study period.

We report the mean, standard deviation, upper and lower measures, as well as total number of observations in Table 1. Notably, economic growth demonstrates the highest average (4.52) with a standard deviation of 0.2101. Renewable energy and technology innovation show significant changes over the study period. While the average of renewable energy shows 3.1908, it shows clear change from 0.383 to 4.990. In the meantime, the technology innovation has also increased remarkably from 0.0953 to 4.2515. Similarly, energy prices also fluctuated considerably from 1.153 to 3.593. Unlike other variable, Women empowerment index reveals slight change over the period, the index indicate movement from 0.741 to 0.961, with average and standard deviation of 0.915 and 0.0343, respectively.

Fig. 2 displays diagnostic evidence of spatial dependence in the Women's Political Empowerment Index across regions. The Moran's I scatter plot (Panel A) shows the standardized regional values of the index on the x-axis and their spatially lagged averages on the y-axis. The positive slope of the fitted regression line indicates clustering of similar values. The calculated Moran's I statistic is **0.459**, suggesting **moderate to strong positive spatial autocorrelation**. In substantive terms, regions with higher female political representation tend to be geographically contiguous, reinforcing the hypothesis that social norms, institutional quality, and governance practices diffuse spatially. Panel B reports the results of the permutation test (199 permutations), confirming that the observed Moran's I is statistically significant. The pseudo p-value of **0.005** and the z-value of **3.8584** reject the null hypothesis of spatial randomness at the 1% significance level. The histogram of permuted Moran's I statistics illustrates that the empirical value (green bar) lies well to the right of the simulated distribution under the null.

This spatial clustering provides a robust justification for the econometric strategy. Specifically, the presence of significant spatial autocorrelation in women's political empowerment validates the inclusion of spatially lagged terms in the **Spatial Durbin Model (SDM)** and **Spatial Autoregressive Model (SAR)** specifications. Incorporating these spatial effects allows the estimation to capture both **direct local impacts** and **indirect spillovers** on electricity costs, aligning with the conceptual framework that emphasizes regional interdependencies in governance and energy outcomes.

Fig. 3 provides evidence of spatial dependence in economy-wide real electricity costs across regions. Panel A depicts the Moran's I scatter plot, with standardized electricity cost residuals on the x-axis and their spatially lagged values on the y-axis. The upward-sloping regression line indicates a positive association, whereby regions with higher (or lower) electricity costs are typically surrounded by regions exhibiting similar cost structures. The estimated Moran's I statistic is **0.421**, which points to **substantial positive spatial autocorrelation**. This suggests that electricity costs are not randomly distributed but rather demonstrate pronounced spatial clustering. Potential drivers of these patterns include shared transmission infrastructure, cross-border regulatory harmonization, and regionally integrated energy markets. Panel B displays the permutation test results (199 permutations). The histogram of simulated Moran's I values under the null hypothesis of spatial randomness shows

Table 1
Descriptive statistics.

Variable	Observations	Mean	Std. Dev.	Min	Max
lnENGCST	660	2.6774	0.3605	1.153	3.593
lnGen-1	660	0.9154	0.0343	0.741	0.961
lnTech	660	2.5579	0.7004	0.095	4.251
lnREN	660	3.1908	0.9725	0.383	4.990
lnGDP	660	4.5249	0.2101	3.954	5.060

Note: The dataset covers 22 European countries over a 30-year period from 1990 to 2019, totaling 660 observations.

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[1] https://stm.cairn.info/journal-of-energy-history-2021-2-page-1e?lang=en.

[2] https://ourworldindata.org/grapher/women-political-empowerment-index.

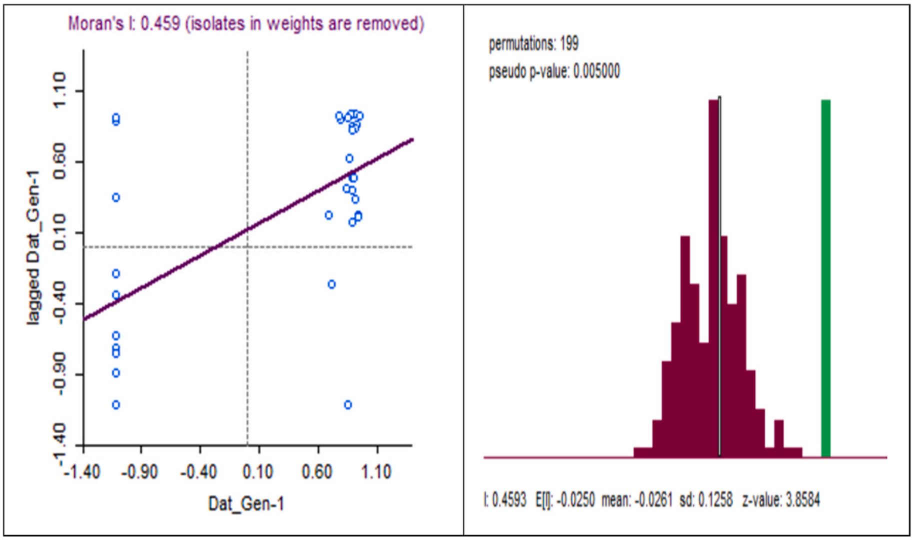

Fig. 2. Spatial autocorrelation for Women's Political Empowerment Index

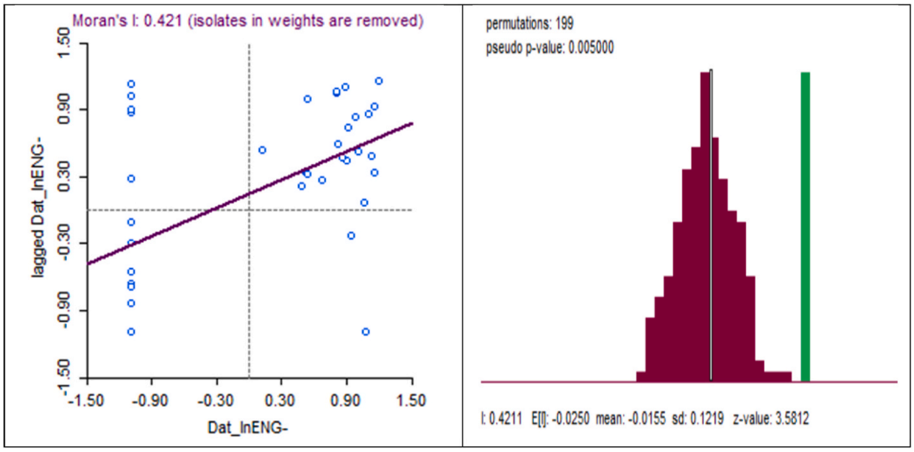

Fig. 3. Spatial autocorrelation for economy-wide real electricity costs

that the observed statistic (green bar) lies far to the right of the simulated distribution. The pseudo p-value of **0.005** and the z-value of **3.5812** reject the null of no spatial autocorrelation at the 1% significance level.

5. Results

In this section, we use the Spatial Durbin Model (SDM) to analyze the relationship between electricity costs and women's empowerment at the spatial level. Our primary goal in this section is to achieve more comprehensive and accurate results by considering not only the internal effects of variables within a region but also their spillover effects on neighbouring regions. This analysis, specific to Europe, provides an important example of spatial dependence due to its high level of economic, technological, and social interaction across countries. In this context, we evaluate not only the direct effects of electricity costs but also their indirect spatial effects, exploring evidence on how policies aimed at women's economic and social empowerment can be made more effective through regional cooperation and coordination.

Despite this potential endogeneity issue, we argue that a significant portion of the endogeneity may be attributable to spatial dependence. Since the Spatial Durbin Model (SDM) explicitly captures spatial interactions by incorporating both endogenous and exogenous spillovers, it constitutes an appropriate and robust framework for estimating the average direct and indirect effects across countries. According to (Beer and Riedl, 2012; Kopczewska et al., 2017), this approach is widely used to reduce bias arising from omitted spatially correlated variables. By including spatial lags of the explanatory variables, the model captures unobserved factors that are spatially correlated with the regressors, thereby mitigating unobserved spatial endogeneity and heterogeneity. Finally, the robustness of the results is assessed using an alternative spatial weight matrix based on the Rook contiguity criterion (Appendix Tables A3 and Table A4). While Queen contiguity defines countries as neighbours when they share either a common border or a single point (vertex), Rook contiguity considers only those that share a common border (edge). Consequently, when all countries in the sample share borders through edges rather than merely at vertices, the Queen and Rook contiguity matrices become identical (Figures A6 and Figure A7). As expected, the SDM and SAR estimations using both Queen and Rook contiguity matrices show very similar results, despite minor differences in magnitude. In addition, the model selection test results based on the Rook contiguity criterion in Table A5 also reject the null hypothesis that the SDM can be reduced to SAR specifications, thereby confirming the SDM as the preferred model. Lastly, pooled OLS estimation is performed as an additional robustness check (Table A6).

We report the estimation results of the Spatial Durbin Model (SDM) assessing the determinants of regional energy costs (lnENG-CST) in Table 2. The model specification accounts for both spatial dependence

Table 2
Spatial Durbin Model (SDM) with direct and indirect effect.

lnENG-CST	Coef.	Std. Err.	z	P > z	[95% Conf.	[Interval]
Main						
lnGen-1	−0.88535*	0.299189	−2.96	0.003	−1.47175	−0.29895
lnTech	0.059058*	0.014985	3.94	0.000	0.029688	0.088428
lnREN	0.016399	0.018594	0.88	0.378	−0.02004	0.052843
lnGDP	1.031557*	0.100624	10.25	0.000	0.834338	1.228775
_cons	−0.95616***	0.546158	−1.75	0.08	−2.02661	0.114295
Wx						
lnGen-1	−2.32214*	0.460429	−5.04	0.000	−3.22457	−1.41972
lnTech	0.123257*	0.021936	5.62	0.000	0.080264	0.16625
lnREN	−0.02784	0.025738	−1.08	0.279	−0.07828	0.022609
lnGDP	0.42936*	0.126364	3.4	0.001	0.18169	0.677029
Spatial						
rho	−0.17946*	0.044896	−4	0.000	−0.26746	−0.09147
Log-likelihood	235.9746					
Variance						
lgt_theta	−2.59492*	0.168428	−15.41	0.000	−2.92503	−2.26481
sigma2_e	0.025726*	0.00138	18.64	0.000	0.02302	0.028431
LR Direct						
lnGen-1	−0.74754**	0.315982	−2.37	0.018	−1.36685	−0.12823
lnTech	0.051631*	0.014954	3.45	0.001	0.022321	0.08094
lnREN	0.020181	0.018629	1.08	0.279	−0.01633	0.056692
lnGDP	1.013863*	0.099862	10.15	0.000	0.818138	1.209589
LR Indirect						
lnGen-1	−1.94266*	0.434845	−4.47	0.000	−2.79494	−1.09038
lnTech	0.102153*	0.020193	5.06	0.000	0.062577	0.14173
lnREN	−0.02913	0.023218	−1.25	0.21	−0.07463	0.016381
lnGDP	0.216375*	0.114375	1.89	0.059	−0.0078	0.440547
LR Total						
lnGen-1	−2.6902*	0.445193	−6.04	0.000	−3.56276	−1.81764
lnTech	0.153784*	0.020386	7.54	0.000	0.113827	0.193741
lnREN	−0.00894	0.020251	−0.44	0.659	−0.04864	0.030748
lnGDP	1.230238*	0.124966	9.84	0.000	0.98531	1.475167

Note: *p < 0.01; **p < 0.5; ***p < 0.1.

and spillover effects from neighbouring regions. The results indicate that lagged women's political empowerment (lnGen-1) exerts a significant negative effect on energy costs (coefficient = −0.885, $p < 0.01$). This suggests that women's political empowerment or participation help to alleviate supply constraints and reduce electricity prices. Technological progress (lnTech) has a significant positive impact (coefficient = +0.059, $p < 0.01$), which may reflect the higher capital costs associated with adopting advanced energy technologies. For the case of technological progress, First, technological adoption in the heterogeneous EU can create competitiveness pressure in the electricity markets by encouraging local utilities and government to upgrade grid infrastructure. These competitiveness and investment-led initiatives improve long-run efficiency that may uplift electricity costs. Secondly, it may also trigger adjustments and regulatory policy. Government may adopt rigid environmental regulations and renewable energy targets to align with technological standards. It may increase short-run production and compliance costs in the EU economies. Thirdly, this may also influence market regulation and energy trade dynamics via potentially shifting electricity supply patterns. Finally, technological adoption often requires scale of economies (infrastructure, labour, regulatory framework) at the initial stage. This transitions temporarily rise the electricity costs. Renewable energy adoption (lnREN) is not statistically significant in this specification. It may be because of several structural characteristics of the energy transition in the EU economies. The deployment of renewable energy has been impacted by regulatory framework and subsidy schemes that temporarily shield renewable generation align with price mechanism in the energy market. On the other side, it may require substantial capital investment in grid infrastructure, balancing mechanism and storage capacity which may upset potential costs reduction in the short run. Moreover, heterogeneity exists across EU economies in term of energy maturity, policy-driven support, and technological adoption. These differences may weaken the significant level of renewable energy. Economic growth (lnGDP) emerges as a strong driver of increased energy costs (coefficient = +1.032, $p < 0.01$), consistent with rising demand pressures accompanying economic expansion.

Spatial spillover effects are substantial and economically relevant. The spatially lagged women's political empowerment shows a large negative spillover effect (coefficient = −2.322, $p < 0.01$), indicating that women's political participation can reduce local costs through improved system reliability and efficacy in decision-making. Conversely, technological progress in neighbouring areas increases local energy costs (coefficient = +0.123, $p < 0.01$), which may result from technology diffusion raising regional input prices or encouraging the adoption of more costly production methods. The spatial spillover of renewable energy adoption is not statistically significant. Economic growth in neighbouring regions exerts a positive and significant spillover effect (+0.429, $p < 0.01$), underscoring the interconnected nature of regional energy markets. The spatial autoregressive coefficient (rho = −0.179, $p < 0.01$) is negative and significant, suggesting that higher energy costs in neighbouring regions are associated with lower local costs, potentially due to substitution effects or reallocation of supply.

The decomposition of long-run effects provides additional insight.

The long-run direct impact of lagged women's political empowerment remains negative and significant (−0.748, $p < 0.05$), while technological progress (+0.052, $p < 0.01$) and GDP (+1.014, $p < 0.01$) exert significant upward pressures. The long-run indirect effects indicate that generation capacity has a substantial negative spillover (−1.943, $p < 0.01$), whereas technological progress (+0.102, $p < 0.01$) and GDP (+0.216, $p < 0.10$) contribute positively. Summing these components, the total long-run effect of lagged generation capacity is strongly negative (−2.690, $p < 0.01$), while technological progress (+0.154, $p < 0.01$) and GDP (+1.230, $p < 0.01$) exert sizeable positive total effects on energy costs.

The model diagnostics, including a log-likelihood value of 235.97 and significant variance estimates, confirm the robustness of the specification. Collectively, these findings underscore the importance of considering spatial interactions when analysing energy cost dynamics. The evidence highlights that women's political empowerment can deliver substantial cost reductions both locally and regionally. In contrast, technological modernization and economic expansion may increase costs, implying trade-offs between efficiency improvements and affordability. These results suggest that coordinated regional policy strategies are essential to maximize the benefits of women's political empowerment while managing the upward pressure on energy prices associated with growth and technological change. We have made a conceptual mapping in Table A1 in Appendix part.

Next, we report the estimation results from the Spatial Autoregressive (SAR) model specification, which captures spatial dependence in regional energy costs while excluding the spatial lags of explanatory variables in Table 3. This approach isolates the extent to which energy costs in EU economies influence local outcomes independently of covariate spillovers. We get the similar results align with SDM analysis. The estimated coefficients indicate that lagged women's political empowerment (lnGen-1) exerts a negative but statistically insignificant effect on energy costs (coefficient = −1.033, $p = 0.226$). This contrasts with the Spatial Durbin Model results reported earlier and suggests that omitting spatial spillovers of covariates reduces the precision of estimates related to capacity investments. Technological progress (lnTech) shows a positive and statistically significant association with energy costs (coefficient = +0.077, $p < 0.05$), consistent with higher capital costs incurred during technology adoption and modernization. Renewable energy adoption (lnREN) remains statistically insignificant. Economic growth (lnGDP) continues to be a key determinant, exhibiting a strong positive effect on energy costs (coefficient = +0.971, $p < 0.01$).

The estimated spatial autoregressive coefficient is negative and significant ($\rho = -0.124$, $p < 0.05$), indicating that higher energy costs are associated with modest reductions in local costs. This negative spatial dependence may reflect substitution effects or supply reallocation across regions when localized price increases occur.

The decomposition of long-run effects further clarifies the direct and indirect contributions of each factor. The long-run direct effect of lagged women's political empowerment remains negative but is not statistically significant (−1.008, $p = 0.253$). Technological progress maintains a positive and significant direct impact (+0.076, $p < 0.05$). Renewable energy adoption continues to exhibit no significant effect on energy costs. Economic growth shows a robust positive direct effect (+0.962, $p < 0.01$).

The long-run indirect effects, which quantify the influence mediated through spatial dependence, show that technological progress is associated with a marginally significant negative spillover effect (−0.009, $p < 0.10$). This suggests that technology improvements in neighbouring regions may exert a small dampening influence on local costs,

Table 3
Spatial Autoregressive Model (SAR) with direct indirect effect.

lnENG-CST	Coef.	Std. Err.	z	P > z	[95% Conf.	[Interval]
Main						
lnGen-1	−1.03331	0.853785	−1.21	0.226	−2.7067	0.640078
lnTech	0.076621**	0.031933	2.4	0.016	0.014034	0.139208
lnREN	0.039126	0.046272	0.85	0.398	−0.05156	0.129817
lnGDP	0.970864*	0.279746	3.47	0.001	0.422573	1.519155
_cons	−0.76259	1.704261	−0.45	0.655	−4.10288	2.577697
Spatial						
rho	−0.12409**	0.050132	−2.48	0.013	−0.22234	−0.02583
Log-pseudo likelihood	208.9562					
Variance						
lgt_theta	−2.5675*	0.223678	−11.48	0.000	−3.0059	−2.1291
sigma2_e	0.027911*	0.00505	5.53	0.000	0.018013	0.03781
LR Direct						
lnGen-1	−1.00795	0.88127	−1.14	0.253	−2.73521	0.719303
lnTech	0.075572**	0.031139	2.43	0.015	0.014541	0.136603
lnREN	0.043238	0.045581	0.95	0.343	−0.0461	0.132574
lnGDP	0.961868*	0.26176	3.67	0.000	0.448828	1.474907
LR Indirect						
lnGen-1	0.114089	0.111966	1.02	0.308	−0.10536	0.333538
lnTech	−0.00854***	0.004685	−1.82	0.068	−0.01772	0.000645
lnREN	−0.00587	0.00657	−0.89	0.372	−0.01875	0.007007
lnGDP	−0.10862**	0.045511	−2.39	0.017	−0.19782	−0.01942
LR Total						
lnGen-1	−0.89386	0.786015	−1.14	0.255	−2.43443	0.646696
lnTech	0.067034**	0.02832	2.37	0.018	0.011528	0.12254
lnREN	0.037368	0.039564	0.94	0.345	−0.04018	0.114912
lnGDP	0.853251*	0.243928	3.5	0.000	0.375162	1.331341

Note: *p < 0.01; **p < 0.5; ***p < 0.1.

potentially due to positive externalities or shared infrastructure benefits. Economic growth displays a significant negative spillover effect (-0.109, $p < 0.05$), implying that higher growth in adjacent areas may mitigate some of the cost pressures arising locally. Other indirect effects are statistically insignificant.

The total long-run impacts combine the direct and indirect effects. Lagged women's political empowerment has an overall negative but non-significant effect on energy costs (-0.894, $p = 0.255$). Technological progress retains a significant positive total effect ($+0.067$, $p < 0.05$), and economic growth maintains a substantial positive total impact ($+0.853$, $p < 0.01$). Renewable energy adoption remains without a discernible influence.

Model diagnostics confirm the robustness of the specification. The estimated log-pseudo likelihood is 208.96, and the variance parameters are highly significant. These results reinforce the importance of accounting for spatial dependence in modelling regional energy cost dynamics. The consistent positive contributions of technological progress and economic growth suggest that modernization and economic expansion may increase cost pressures, underscoring the need for complementary measures to enhance affordability. Furthermore, the presence of negative spatial spillovers highlights that coordinated regional policies may partially offset localized increases in energy costs.

Last, we also report the results of the model selection tests, incorporating a specification that includes both spatial lag dependence and spatial lags of explanatory variables in Table 4. This approach allows comparison of alternative spatial econometric models and helps assess the robustness of the estimated relationships.

The estimated coefficients are largely consistent with the previous Spatial Durbin Model results. Lagged women's political empowerment (lnGen-1) remains a significant negative determinant of energy costs (coefficient $= -0.874$, $p < 0.01$), underscoring the robust cost-reducing effect of investments in generation capacity. Technological progress (lnTech) exhibits a positive and statistically significant association with energy costs (coefficient $= +0.060$, $p < 0.01$), reinforcing earlier evidence that technology adoption may initially raise costs. Renewable energy adoption (lnREN) remains statistically insignificant. Economic growth (lnGDP) continues to exert a strong positive impact (coefficient $= +1.093$, $p < 0.01$).

The spatially lagged explanatory variables highlight substantial spillover effects. Lagged women's political empowerment in neighbouring regions exerts a large negative spillover (coefficient $= -2.340$, $p < 0.01$), consistent with cross-border benefits from capacity expansion. Technological progress in neighbouring areas increases local energy costs (coefficient $= +0.123$, $p < 0.01$), suggesting diffusion of higher-cost technologies or competitive effects. Renewable energy adoption remains insignificant in spatial spillovers. Economic growth in neighbouring regions is positively associated with local energy costs (coefficient $= +0.390$, $p < 0.01$), again indicating the interconnected nature of energy markets.

The estimated spatial autoregressive coefficient is negative and statistically significant ($\rho = -0.188$, $p < 0.01$), confirming the presence of negative spatial dependence. This suggests that higher energy costs in neighbouring regions are associated with reductions in local costs, possibly reflecting substitution or market rebalancing effects. Model selection is further supported by the Chi-squared test of spatial dependence. The reported Chi-squared statistic ($\text{Chi}^2 = 57.78$, $p < 0.01$) strongly rejects the null hypothesis of no spatial dependence, confirming the appropriateness of spatial modelling over simpler non-spatial specifications. The significant variance estimate ($\sigma_e^2 = 0.025$, $p < 0.01$) reinforces the robustness of the model.

Overall, these results provide compelling evidence that both direct regional factors and spatial spillovers play a significant role in shaping energy costs. The model selection tests and diagnostics indicate that the Spatial Durbin Model remains the preferred specification, capturing the complex interdependencies in regional energy markets more effectively than alternative models.

6. Conclusion

This study provides new evidence on the determinants of energy costs by applying spatial econometric techniques to disentangle the direct and spillover effects of women's political empowerment, technological progress, renewable energy adoption, and economic growth. The results consistently demonstrate that spatial interactions play a significant role in shaping energy market outcomes, with important implications for both energy policy and gender-responsive development strategies. The results indicate that greater inclusion of women in political decision-making processes may improve the governance and allocation of energy resources, contributing to cost reductions that extend beyond local boundaries. In contrast, technological progress is associated with a positive role on energy costs locally and through spatial spillovers, reflecting the initial capital intensity and adjustment costs linked to modernization. Economic growth emerges as a convincing driver of higher energy costs, consistent with increased

Table 4
Model selection test.

lnENG-CST	Coef.	Std. Err.	z	P > z	[95% Conf.	[Interval]
Main						
lnGen-1	−0.87364*	0.295352	−2.96	0.003	−1.45252	−0.29476
lnTech	0.060389*	0.014823	4.07	0.000	0.031337	0.089441
lnREN	0.018621	0.018624	1	0.317	−0.01788	0.055124
lnGDP	1.093337*	0.100031	10.93	0.000	0.897279	1.289395
Wx						
lnGen-1	−2.3396*	0.454767	−5.14	0.000	−3.23092	−1.44827
lnTech	0.123371*	0.021674	5.69	0.000	0.08089	0.165853
lnREN	−0.03073	0.025677	−1.2	0.231	−0.08105	0.0196
lnGDP	0.389734*	0.125462	3.11	0.002	0.143833	0.635635
Spatial						
rho	−0.18755*	0.044702	−4.2	0.000	−0.27516	−0.09993
Variance						
sigma2_e	0.024904*	0.001314	18.95	0.000	0.022327	0.02748
Chi^2 (4)	57.78*			0.000		

Note: *p < 0.01; **p < 0.5; ***p < 0.1.

demand pressures accompanying expansion. These patterns are consistent across model specifications and are most comprehensively captured in the SDM and SAR, which fully accounts for spatial dependence and covariate spillovers.

From a policy perspective, several implications emerge. First, strengthening women's political participation and representation can yield significant co-benefits for energy affordability, supporting recent arguments that gender empowerment enhances governance quality and allocative efficiency. Regional coordination and capacity-building initiatives that promote women's leadership in energy policymaking may further amplify these positive spillover effects. Second, while technological upgrades are essential for sustainability and efficiency improvements, they can impose short-run cost burdens on consumers. Policymakers should consider complementary measures, such as transitional subsidies or demand management programs, to ease adjustment costs. Third, the consistent upward pressure of economic growth on energy costs underscores the need to integrate demand-side management and supply diversification strategies into long-term planning to maintain affordability as economies expand. Finally, this study highlights the critical importance of modelling spatial dependence in energy cost analyses. Omitting spatial interactions risks underestimating indirect impacts and misrepresenting policy effectiveness. In addition, the EU economies may consider gender inclusivity metrics into national energy affordability targets that ensure women's political empowerment in regulatory decision for energy sector performance. Secondly, the EU economies also strength and promote leadership training programs for women related to energy regulatory agencies and public utilities that enhance accountability, transparency, and policy effectiveness. Thirdly, promoting regional cooperation in energy governance to amplify positive spillovers in the EU economies that integrate cross-border electricity market and policy mechanism. These approaches can help EU economies positive spillover and improve overall affordability and sustainability simultaneously.

Future research could build on this framework by incorporating dynamic spatial models or exploring interactions between gender empowerment, institutional quality, and energy sector outcomes. Overall, these findings suggest that achieving affordable, reliable, and inclusive energy provision requires not only technological and economic progress but also gender-responsive governance and spatially coordinated policy approaches that leverage the broader benefits of women's political empowerment. Although this study significantly extends the literature, several limitations remain. The sample contains 22 countries and excludes some important EU members due to data constraints, which may bias the results toward data-rich economies. In addition, the time frame (1990–2019) may not capture the most recent global and regional energy-related developments. Lastly, the empirical models assume that spillovers operate primarily through geographic contiguity, thus overlooking alternative transmission channels such as digital connectivity and other non-spatial networks. Future research could address these limitations by incorporating broader country coverage, more recent data, and alternative measures of spatial or network interdependence.

Consent to participate

All the researchers or all co-authors have positively agreed to participate this research work effectively and contribute drastically.

Consent to publish

All are agree to publish this work in this journal ethically.

Ethical approval

This manuscript doesnot harm any animals or human beings or any institutions.

Availability of data and materials

All data and materials will be available as per the request of the authors.

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TableA1

Economic analysis aligns with conceptual mapping.

Conceptual	Citations	Implications
Women's Political Empowerment → Better Governance (Local Direct Effects)	- Dollar et al. (2001): Women reduce corruption. - -Chattopadhyay and Duflo (2004): Women invest more in public goods. - -UN Women (2014): Women improve cost-effective delivery. - -Post and Byron (2015); Terjesen et al. (2009): Women enhance oversight and accountability.	Justifies including **lnGen-1** as a regressor and expecting negative coefficients on energy costs. Direct effects capture local governance improvements.
Better Governance → Lower Electricity Costs	- Sovacool (2012): Good governance improves efficiency. - -Estache and Goicoechea (2005): Weak institutions raise costs. - - World Bank (2018): Regulatory capacity lowers prices.	Strengthens interpretation of negative direct effects of lnGen-1 on lnENG-CST.
Technology & Renewable Integration → Upward Cost Pressure (Local Direct Effects)	- Atil et al. (2020): Nonlinear pass-through. - -Borenstein (2012): High initial investment costs. - -IEA (2020): Capital-intensive grid integration. - -Blázquez et al. (2017): Subsidy distortions.	Justifies including **lnTech** and **lnREN**. Expect positive coefficients in short run.
Economic Growth → Higher Demand and Prices	- Sadorsky (2000): Demand-pull effect. - - Newell et al. (2019): Economic growth tightens supply. - - Bekhet and Yusop (2009): Growth-energy price link.	Justifies inclusion of **lnGDP**. Expect positive direct effects.
Spillover Channels (Indirect Effects in SDM/Spatial Lag in SAR)	- LeSage and Pace (2009): Spatial dependence in energy markets. - -Buntaine and Parks (2013): Institutional spillovers. - -UN Women (2014): Policy diffusion across regions. - -Hoogendoorn et al. (2013): Cross-region knowledge sharing.	Provides rationale for using SDM and SAR. Indirect effects and spatial autocorrelation (rho) quantify spillovers.
Aggregate Effects (Total Impact)	- Carley and Konisky (2020): Equity impacts can cross regions. - -Sovacool (2012): Interlinked governance and market dynamics.	Total effects in SDM (direct + indirect) reflect broad system influence of gender empowerment and other drivers.

TableA2

List of EU countries with a schematic diagram of adjacent space weight matrix

1	Norway	2	5							
2	Sweden	1	5							
3	Germany	4	6	11	14	15	17	19	21	22
4	Netherlands	3	14							
5	Finland	1	2							
6	France	3	7	14	15	18	21			
7	Italy	6	11	12	15					
8	Estonia	9								
9	Latvia	8	10							
10	Lithuania	9	22							
11	Austria	3	7	12	13	15	16	17		
12	Slovenia	7	11	13						
13	Hungary	11	12	16						
14	Belgium	3	4	6	21					
15	Switzerland	3	6	7	11					
16	Slovakia	11	13	17	22					
17	Czechia	3	11	16	22					
18	Spain	6	20							
19	Denmark	3								
20	Portugal	18								
21	Luxembourg	3	6	14						
22	Poland	3	10	16	17					

Table A3

Spatial Durbin Model (SDM) with direct and indirect effect based on Rook weight matrix.

lnENG-CST	Coef.	Std. Err.	z	P > z	[95% Conf.	Interval]
Main						
lnGen-1	−1.25563	0.335889	−3.74	0.000	−1.91396	−0.5973
lnTech	0.053678	0.016337	3.29	0.001	0.021659	0.085697
lnREN	0.020213	0.020731	0.98	0.33	−0.02042	0.060845
lnGDP	1.106806	0.110288	10.04	0.000	0.890644	1.322967
_cons	−0.66698	0.56132	−1.19	0.235	−1.76715	0.433182
Wx						
lnGen-1	−2.49676	0.49577	−5.04	0.000	−3.46845	−1.52507
lnTech	0.137072	0.024502	5.59	0.000	0.089049	0.185096
lnREN	−0.0159	0.02904	−0.55	0.584	−0.07282	0.041015
lnGDP	0.380152	0.136041	2.79	0.005	0.113517	0.646787
Spatial rho	−0.17259	0.046667	−3.7	0.000	−0.26405	−0.08112
Variance						
lgt_theta	−2.5562	0.170555	−14.99	0.000	−2.89048	−2.22192
sigma2_e	0.025748	0.001451	17.75	0.000	0.022904	0.028592
Log-likelihood	209.9616					
LR_Direct						
lnGen-1	−1.1149	0.353794	−3.15	0.002	−1.80832	−0.42147
lnTech	0.045589	0.016114	2.83	0.005	0.014006	0.077171
lnREN	0.023483	0.020762	1.13	0.258	−0.01721	0.064175
lnGDP	1.093306	0.110001	9.94	0.000	0.877709	1.308903
LR_Indirect						
lnGen-1	−2.05438	0.471387	−4.36	0.000	−2.97828	−1.13048
lnTech	0.116126	0.022605	5.14	0.000	0.071821	0.16043
lnREN	−0.019	0.025959	−0.73	0.464	−0.06988	0.031874
lnGDP	0.166187	0.123903	1.34	0.18	−0.07666	0.409032
LR_Total						
lnGen-1	−3.16927	0.485063	−6.53	0.000	−4.11998	−2.21857
lnTech	0.161714	0.024103	6.71	0.000	0.114473	0.208956
lnREN	0.004478	0.022338	0.2	0.841	−0.0393	0.048259
lnGDP	1.259493	0.131685	9.56	0.000	1.001394	1.517591

Note: $^{*}p < 0.01$; $^{**}p < 0.5$; $^{***}p < 0.1$.

Table A4

Spatial Autoregressive Model (SAR) with direct and indirect effect based on Rook weight matrix.

(continued on next column)

Table A4 (*continued*)

lnENG-CST	Coef.	Std. Err.	z	P > z	[95% Conf.	Interval]
Main						
lnGen-1	−1.51821	0.907936	−1.67	0.094	−3.29773	0.261317
lnTech	0.0668	0.02888	2.31	0.021	0.010198	0.123403
lnREN	0.055308	0.050297	1.1	0.271	−0.04327	0.153888
lnGDP	1.038405	0.299595	3.47	0.001	0.45121	1.6256
_cons	−0.67853	1.756317	−0.39	0.699	−4.12085	2.763788
Spatial rho	−0.11231	0.056242	−2	0.046	−0.22255	−0.00208
Variance						
lgt_theta	−2.52488	0.226347	−11.15	0.000	−2.96851	−2.08124
sigma2_e	0.02811	0.00519	5.42	0.000	0.017937	0.038282
Log-pseudolikelihood	183.5134					
LR_Direct						
lnGen-1	−1.49208	0.935372	−1.6	0.111	−3.32538	0.341215
lnTech	0.065745	0.02823	2.33	0.02	0.010416	0.121074
lnREN	0.059989	0.049389	1.21	0.225	−0.03681	0.156789
lnGDP	1.025161	0.278018	3.69	0.000	0.480256	1.570066
LR_Indirect						
lnGen-1	0.14644	0.114978	1.27	0.203	−0.07891	0.371792
lnTech	−0.00674	0.004328	−1.56	0.119	−0.01522	0.001741
lnREN	−0.00721	0.007178	−1	0.315	−0.02128	0.006857
lnGDP	−0.10508	0.052537	−2	0.045	−0.20805	−0.00211
LR_Total						
lnGen-1	−1.34564	0.861281	−1.56	0.118	−3.03372	0.34244
lnTech	0.059003	0.026064	2.26	0.024	0.007918	0.110088
lnREN	0.052777	0.043273	1.22	0.223	−0.03204	0.137591
lnGDP	0.920078	0.264346	3.48	0.001	0.40197	1.438187

Note: $^{*}p < 0.01$; $^{**}p < 0.5$; $^{***}p < 0.1$.

Table A5

Model selection test based on Rook weight matrix.

lnENG CST	Coef.	Std. Err.	z	P > z	[95% Conf.	Interval]
Main						
lnGen-1	−1.22795	0.331374	−3.71	0.000	−1.87743	−0.57847
lnTech	0.054467	0.016147	3.37	0.001	0.02282	0.086115
lnREN	0.023268	0.020835	1.12	0.264	−0.01757	0.064105
lnGDP	1.186845	0.109494	10.84	0.000	0.972241	1.401449
Wx						
lnGen-1	−2.53431	0.489085	−5.18	0.000	−3.4929	−1.57573
lnTech	0.137427	0.024175	5.68	0.000	0.090045	0.18481
lnREN	−0.01924	0.029069	−0.66	0.508	−0.07622	0.037732
lnGDP	0.322223	0.134929	2.39	0.017	0.057767	0.586679
Spatial rho	−0.17996	0.046449	−3.87	0.000	−0.271	−0.08892
Log-likelihood						
Variance						
sigma2_e	0.024841	0.001374	18.08	0.000	0.022147	0.027535
chi2 (4)	57.08			0.000		

Note: $^{*}p < 0.01$; $^{**}p < 0.5$; $^{***}p < 0.1$.

Table A6

Pooled OLS estimator

lnENG-CST	Coef.	Std. Err.	t	P > t	[95% Conf.	Interval]
lnGen-1	−0.71819	0.486219	−1.48	0.14	−1.67292	0.236551
lnTech	0.06319	0.019803	3.19	0.001	0.024306	0.102075
lnREN	−0.05406	0.015565	−3.47	0.001	−0.08462	−0.02349
lnGDP	−0.16701	0.071635	−2.33	0.02	−0.30767	−0.02635
_cons	4.101452	0.409764	10.01	0.000	3.296842	4.906063

Note: $^{*}p < 0.01$; $^{**}p < 0.5$; $^{***}p < 0.1$.

CRediT authorship contribution statement

Hemachandra Padhan: Conceptualization, Investigation, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing. **Mustafa Kocoglu:** Conceptualization, Data curation, Formal analysis, Supervision, Validation, Writing – original draft, Writing – review & editing. **Mohammed Alnour:** Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft. **Ahmet Tanc:** Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The standard no conflict of interest statement.

Appendix

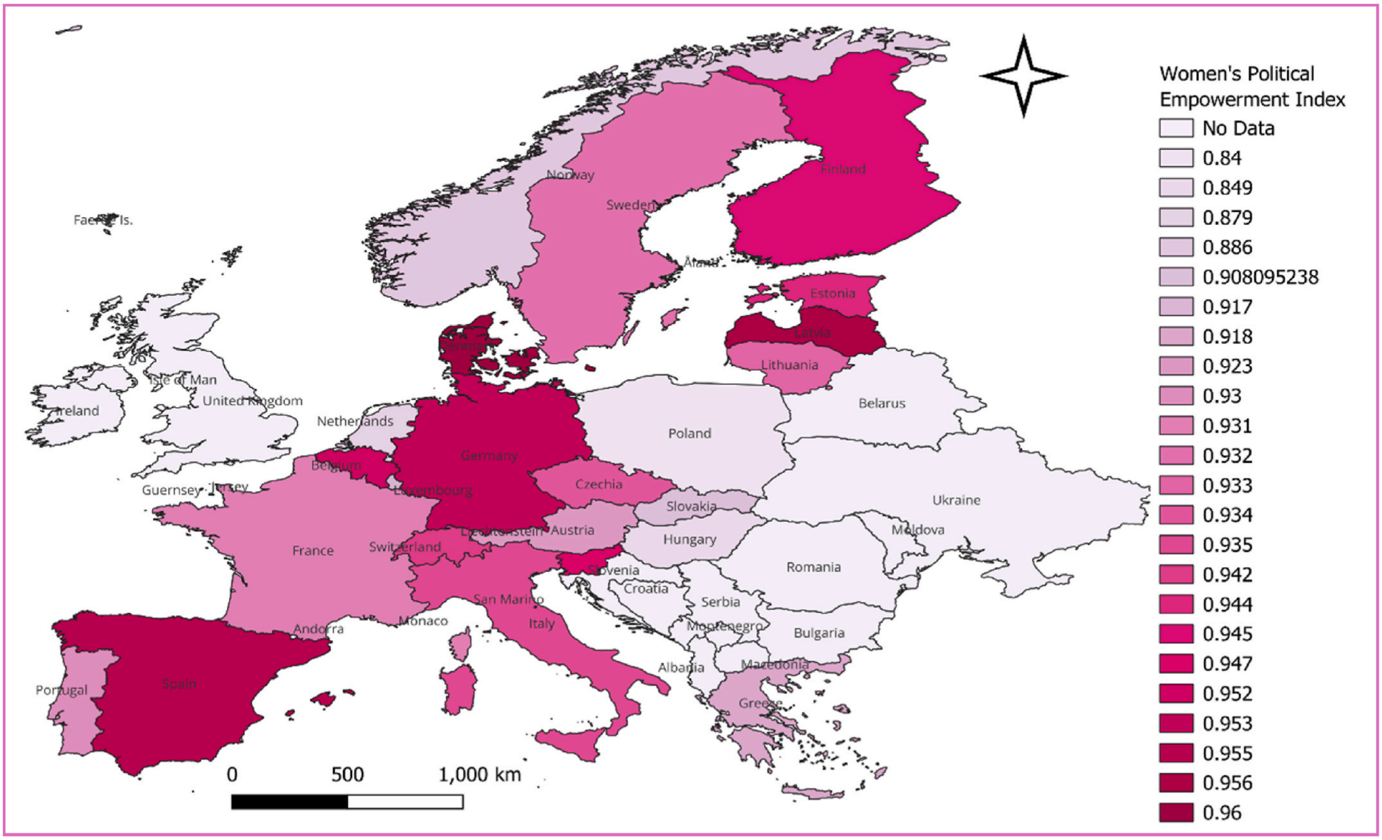

Figure A1. Spatial distribution of Women's political empowerment status

maps the regional variation in the Women's Political Empowerment Index across European countries. The index is a composite measure capturing women's representation in legislative bodies, executive positions, and other formal political institutions. Higher values (darker shades) indicate greater levels of gender-inclusive political participation. The figure demonstrates **substantial spatial heterogeneity**. Notably, the Nordic countries (Finland, Estonia), parts of Western Europe (Germany, Spain, Portugal), and select Central European nations exhibit the **highest empowerment scores**, often exceeding 0.95. Conversely, several Eastern and Southeastern European countries report relatively **lower values**, indicating persistent gaps in women's political representation.

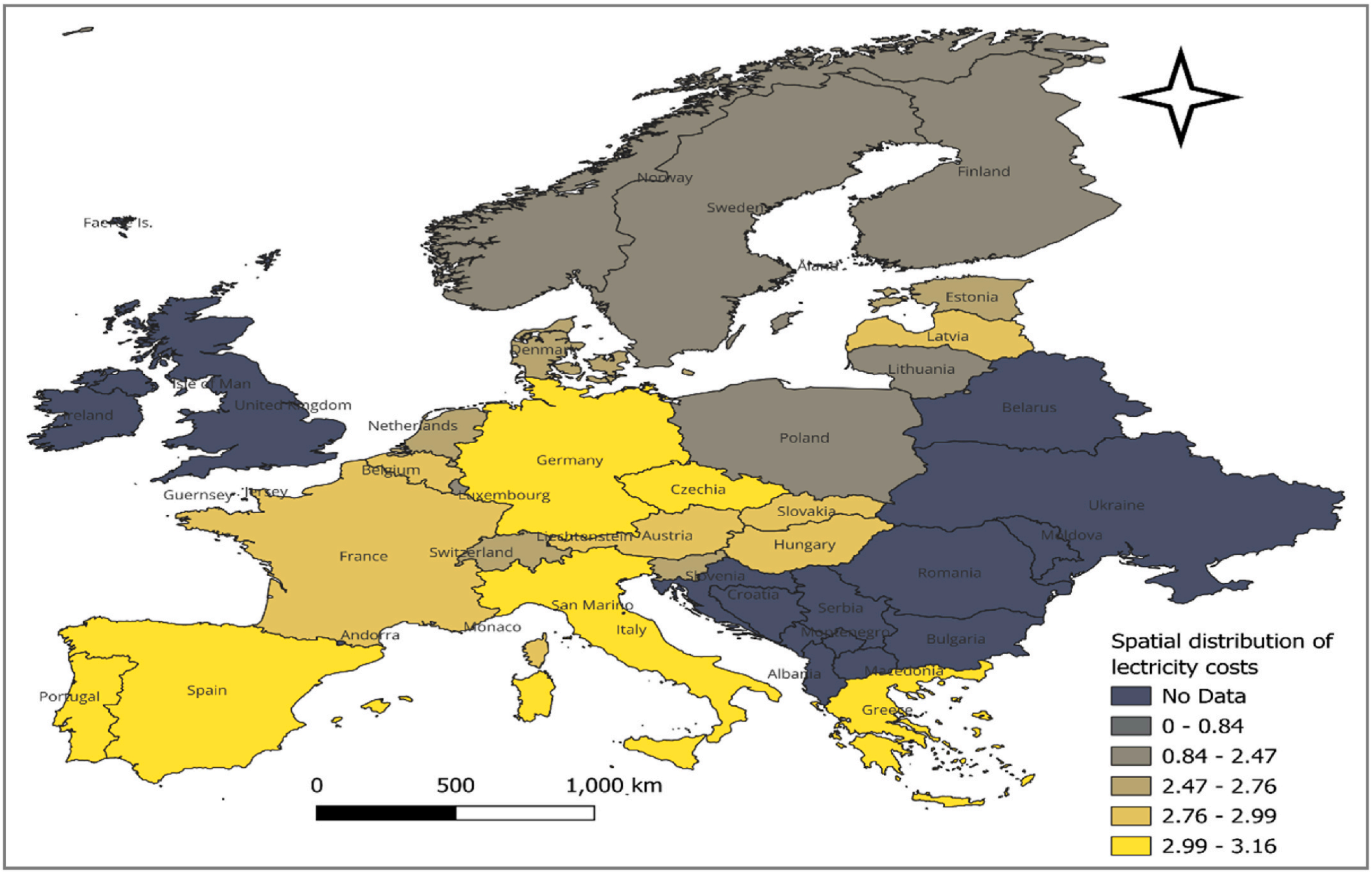

Figure A2. Spatial distribution of economy-wide real electricity costs

illustrates the spatial distribution of **economy-wide real electricity costs** (logged and normalized) across European countries. The map categorizes regions into five intervals, with darker shades representing **lower electricity costs** and lighter shades indicating **higher cost burdens**. Southern and Western European countries—including **Spain, France, Italy, and Germany**—exhibit relatively **higher electricity costs**, falling in the upper quantiles (2.76–3.16). These regions may experience upward pricing pressures due to high retail tariffs, renewable energy surcharges, and regulatory cost pass-throughs (Bekhet and Yusop, 2009; IEA, 2020). In contrast, **Eastern European countries** such as **Romania, Ukraine, and Bulgaria** fall within the **lowest cost category (0–0.84),** reflecting lower consumer prices, possibly due to price subsidies, state control, or lagging liberalization of energy markets. The spatial heterogeneity suggests that electricity costs are shaped by both **domestic policy choices** and **regional economic integration dynamics**. When juxtaposed with Figure A1 (women's political empowerment), this map provides preliminary visual evidence for **spatial misalignment**—regions with high empowerment scores do not always correspond to low electricity costs, underscoring the need for formal spatial econometric analysis.

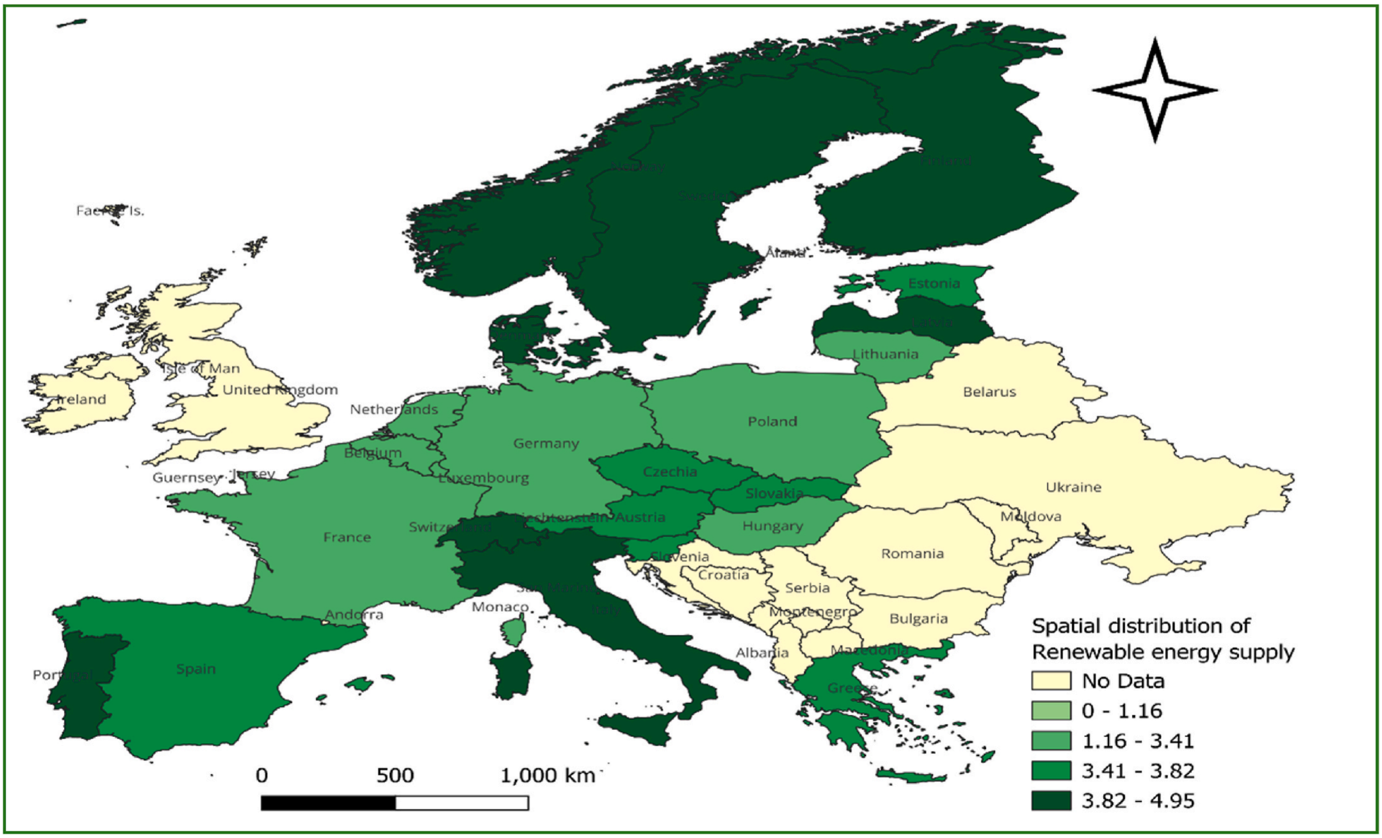

Figure A3. Spatial distribution of renewable energy supply, % total energy supply.

presents the spatial variation in the **share of renewable energy in total energy supply** across European countries. The map divides countries into five categories, from very low (0–1.16%) to very high (3.82–4.95%) penetration rates. The **Nordic countries (Norway, Sweden, Finland)** and parts of **Southern Europe (Spain, Portugal)** exhibit the **highest shares of renewables**, reflecting their long-standing investments in hydropower, wind, and solar technologies. Conversely, countries in **Eastern Europe, including Romania, Bulgaria, Moldova, and Ukraine**, appear in the lowest quantiles, indicating more carbon-intensive energy systems and slower integration of renewable sources. This spatial heterogeneity underpins one of the study's central premises: **technological and institutional drivers of renewable energy deployment are not randomly distributed, but spatially clustered**. The clustering raises the possibility of **positive spillovers** via technology diffusion, market integration, and regional policy emulation (see: Atil et al., 2020; IEA, 2020).

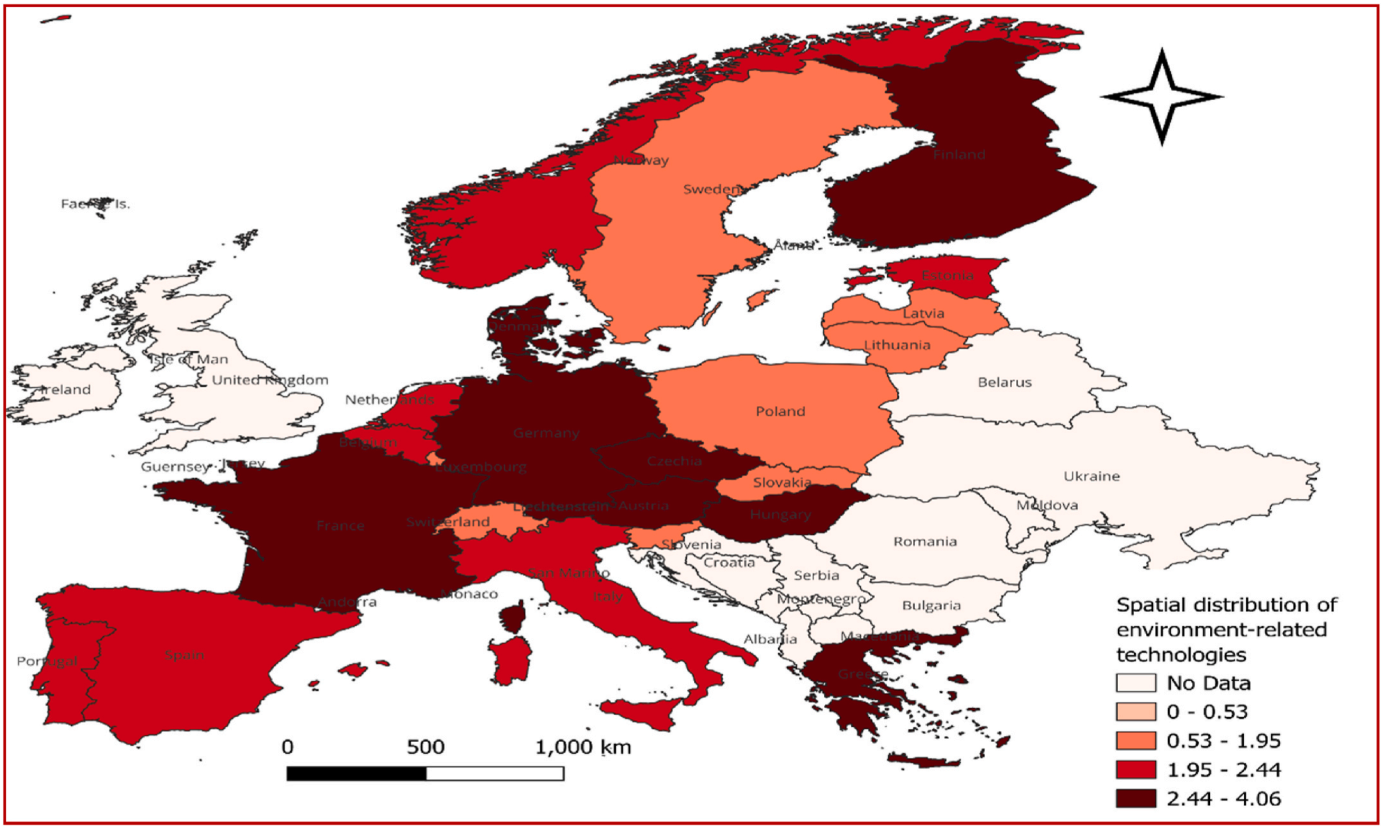

Figure A4. Spatial distribution of environment-related technologies, % all technologies

illustrates the **spatial heterogeneity in the development and diffusion of environment-related technologies,** expressed as a percentage of total technological activity (e.g., patents, innovation outputs) across European countries. The map reveals a clear **Northwest–Southeast gradient: Germany, France, Switzerland, and the Nordic countries** consistently record **the highest shares (2.44–4.06%),** reflecting their advanced industrial capabilities, strong environmental policy frameworks, and substantial public R&D support. In contrast, **Eastern and Southeastern Europe** (Romania, Bulgaria, Moldova, Ukraine) exhibit markedly **lower shares (0–0.53%),** consistent with resource constraints, weaker institutional capacity, and delayed technology adoption. Intermediate levels are observed in **Southern Europe (Italy, Spain, Portugal)** and parts of **Central Europe**, indicating uneven progress in environmental technological upgrading.

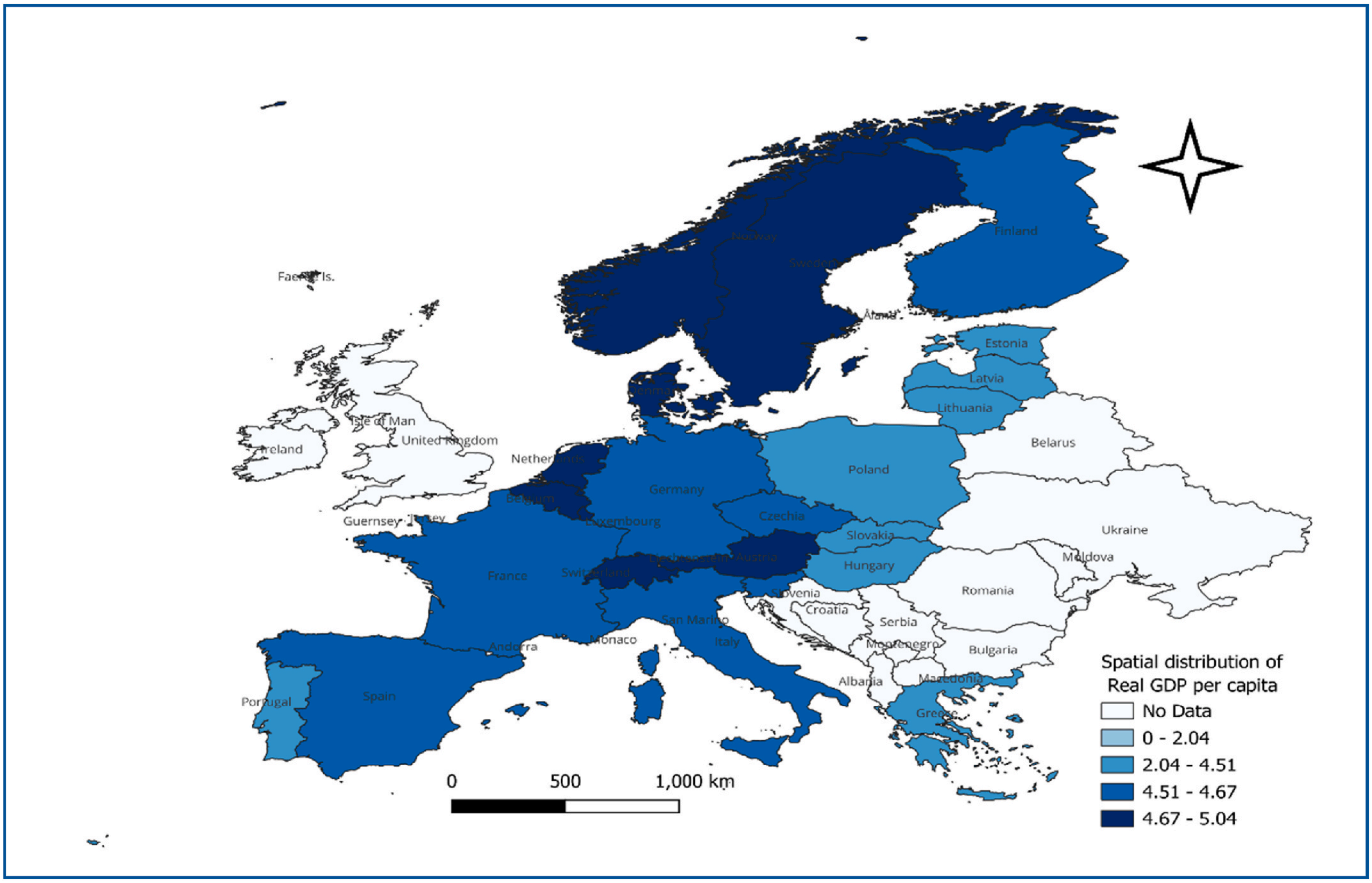

Figure A5. Spatial distribution of real GDP per capita
presents the spatial distribution of real GDP per capita across European countries. High-income clusters are observed in Western and Northern Europe—particularly in Switzerland, Germany, Austria, and the Nordic countries—while lower-income regions are concentrated in Eastern and Southeastern Europe. This spatial heterogeneity in income levels is crucial in understanding disparities in energy affordability, renewable energy investment, and electricity infrastructure development. High-income economies tend to have greater fiscal and institutional capacity to support clean energy transitions and deploy advanced technologies, whereas lower-income countries may face constraints that hinder sustainable energy adoption.

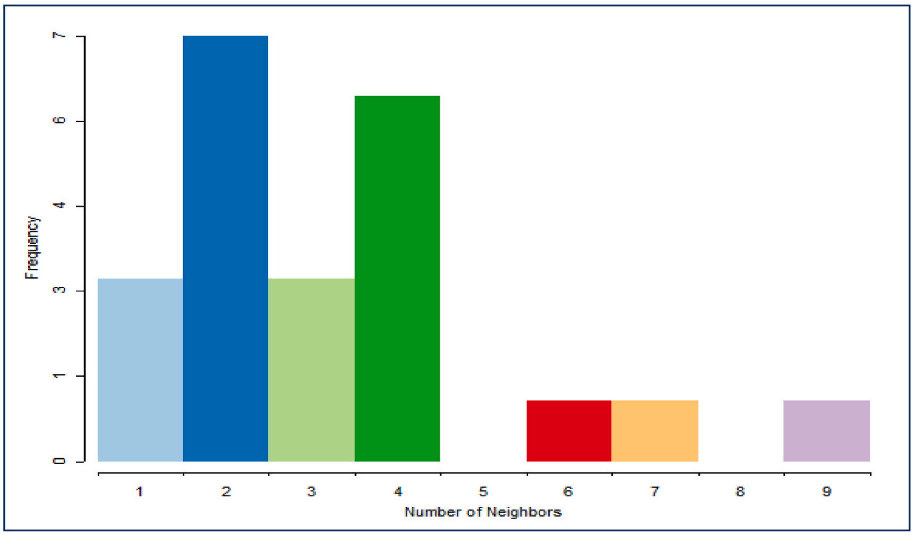

Fig. A6. Weight matrix based on queen contiguity criteria.

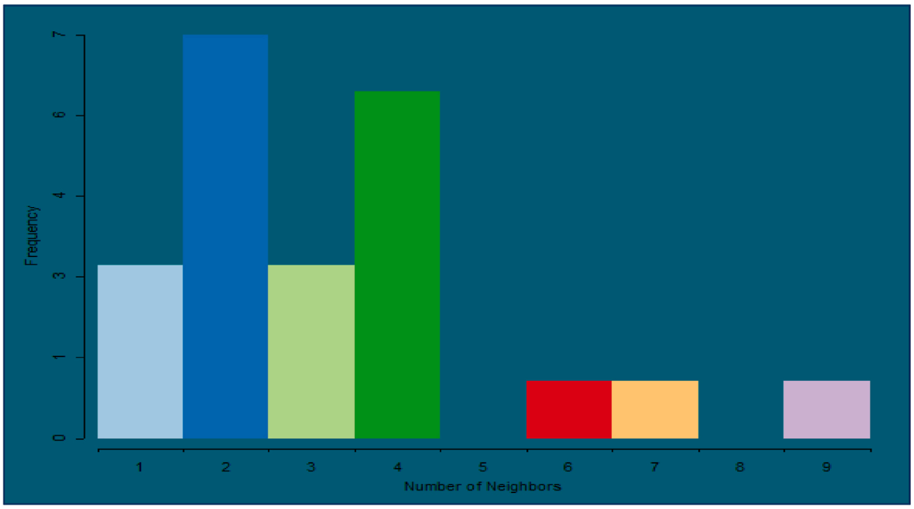

Fig. A7. Weight matrix based on rook contiguity criteria.

Data availability

Data will be made available on request.

References

Anselin, L., 1988. Lagrange multiplier test diagnostics for spatial dependence and spatial heterogeneity. Geogr. Anal. 20 (1), 1–17.

Atil, A., Lahiani, A., Nguyen, D.K., 2020. Energy markets and economic activity: a time-varying analysis of the role of technological innovation. Energy Econ. 86, 104650.

Beer, C., Riedl, A., 2012. Modelling spatial externalities in panel data: the spatial durbin model revisited. Regional Science 91 (2), 299–319.

Bekhet, H.A., Yusop, N.Y.M., 2009. Assessing the relationship between oil prices, energy consumption, and macroeconomic performance in Malaysia: cointegration and vector error correction model (VECM) approach. Energy 34 (10), 2870–2876.

Bloom, N., Mahajan, A., McKenzie, D., Roberts, J., 2010. Why do firms in developing countries have low productivity? Am. Econ. Rev. 100 (2), 619–623.

Blázquez, L., Boogen, N., Filippini, M., 2017. The role of renewable energy in the electricity price formation: an econometric analysis. Energy Econ. 63, 178–187.

Borenstein, S., 2012. The private and public economics of renewable electricity generation. J. Econ. Perspect. 26 (1), 67–92.

Borenstein, S., Davis, L.W., 2016. The Distributional Effects of U.S. Clean Energy Tax Credits. in Tax Policy and the Economy, vol. 30. University of Chicago Press, pp. 191–234. https://doi.org/10.1086/685597, 1.

Buntaine, M.T., Parks, B.C., 2013. When do environmentally focused assistance projects achieve their objectives? Evidence from world bank post-project evaluations. Glob. Environ. Polit. 13 (2), 65–88.

Carley, S., Konisky, D.M., 2020. The justice and equity implications of the clean energy transition. Nat. Energy 5 (8), 569–577.

Chattopadhyay, R., Duflo, E., 2004. Women as policy makers: evidence from a randomized policy experiment in India. Econometrica 72 (5), 1409–1443.

Del Río, P., Mir-Artigues, P., 2014. A cautionary tale: spain's solar PV investment bubble. International Journal of Sustainable Energy Planning and Management 2, 15–28.

Dollar, D., Fisman, R., Gatti, R., 2001. Are women really the "fairer" sex? Corruption and women in government. J. Econ. Behav. Organ. 46 (4), 423–429.

Estache, A., Goicoechea, A., 2005. A "Research" Database on Infrastructure Economic Performance. World Bank Policy Research Working. *Paper No. 3643*.

Guo, Z., Ho, C.S., Ling, G.H.T., Rashid, M.F., 2025. Spatial spillover heterogeneity and moderated effects of the digital economy on agricultural carbon emissions: evidence from 30 Chinese provinces. Environ. Dev. Sustain. 1–31.

Hoogendoorn, S., Oosterbeek, H., van Praag, M., 2013. The impact of gender diversity on the performance of business teams: evidence from a field experiment. Manag. Sci. 59 (7), 1514–1528.

Hossain, M.E., Kanwal, S., Fatima, S., Önden, A., Rehman, M.Z., Alnour, M., 2025. Monitoring the spatial spillover effects of wildfire carbon emissions and urban settlements on biodiversity loss in Sub-Saharan Africa. Int. J. Sustain. Dev. World Ecol. 32 (7), 757–774.

International Energy Agency, 2020. Energy and Gender: Promoting Inclusion for Sustainable Development. IEA, Paris.

Kopczewska, K., Kudła, J., Walczyk, K., 2017. Strategy of spatial panel estimation: spatial spillovers between taxation and economic growth. Applied Spatial Analysis and Policy 10 (1), 77–102.

LeSage, J., Pace, R.K., 2009. Introduction to Spatial Econometrics. CRC Press.

Miller, G., 2008. Women's suffrage, political responsiveness, and child survival in American history. Q. J. Econ. 123 (3), 1287–1327.

Newell, R.G., Raimi, D., Aldana, G., 2019. Global energy outlooks comparison: methods and insights. Energy Econ. 81, 535–559.

Post, C., Byron, K., 2015. Women on boards and firm financial performance: a meta-analysis. Acad. Manag. J. 58 (5), 1546–1571.

Sadorsky, P., 2000. The empirical relationship between energy futures prices and exchange rates. Energy Econ. 22 (2), 253–266.

Sovacool, B.K., 2012. The political economy of energy poverty: a review of key challenges. Energy Sustain. Dev. 16 (3), 272–282.

Terjesen, S., Sealy, R., Singh, V., 2009. Women directors on corporate boards: a review and research agenda. Corp. Govern. Int. Rev. 17 (3), 320–337.

UN Women, 2014. World Survey on the Role of Women in Development 2014: Gender Equality and Sustainable Development. https://www.unwomen.org/en/digital-library/publications/2014/10/world-survey-2014.

United Nations, 2020. World Survey on the Role of Women in Development 2019: Why Addressing Women's Unpaid Care Work Matters for Sustainable Development. United Nations.

World Bank, 2018. Regulatory Indicators for Sustainable Energy (RISE) 2018: Sustainable Energy Policies. World Bank Publications.