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TITOLO DELLA TESI
Renewable Energy Transitions in the European Union: From Policy Foundations to Spatial Dynamics and War-Driven Resilience

SUPERVISORE DI TESI
Chiar.ma Prof.ssa. Luisa Scaccia
Chiar.mo Prof. Alfonso Carfora

DOTTORANDO
Dott. Ismail Abdallah

COORDINATORE
Chiar.ma Prof. ssa. Margherita Scoppola

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Dipartimento di Economia e Diritto

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Preface

Writing the thesis has been a professional and personal journey of growth, research, and reflection. My thesis reflects my academic dedication to understand energy transition in the European context in addition to the support, patience, and motivation of those who have accompanied me in this journey. First, I would like to express my gratitude to my supervisors, Professor Luisa Scaccia and Professor Alfonso Carfora for their guidance and constructive feedback. Their insructions and feedback were very helpful and supportive for stregthening my critical thinking.

From the bottom of my heart, I would like to thank the University of Macerata, especially the Department of Economics and Law and my former professors: Laurent Lambert, Nizar Jouini, Ammar Shamileh, Rabia Naguib, and Marwa Farag at Doha Institute for Graduate Studies for their support and for providing encouragement and academic consulting to finish the research. I am also very grateful to my family and friends for their unlimited support and belief in me during the journey. Their encouragement helped me to be consistent in every challenge. Finally, I dedicate this work to all who supported me directly or indirectly and to all who had a belief that this thesis can help societies to be more sustainable and resilient in the future. Thank you all.

Ismail Abdallah
University of Macerata, 2025

Contents

Introduction

The European Union stands at a crossroads in the Anthropocene, where human activities increasingly threaten planetary boundaries. The Great Acceleration since 1950, marked by exponential growth in emissions and resource use, has breached safe limits as underscored by the IPCC's 2023 report calling for a 50 percent emission cut by 2030 to maintain the 1.5 degree C threshold.

Energy transitions historically gradual and complex processes Geels2002,Sovacool2016,Fouquet2010 require both structural reforms and external shocks to accelerate change. Within this context, the European Green Deal (2019) and Fit for 55 (2021) marked the EU's strongest policy commitment yet, targeting a 55

This thesis brings together three interlinked essays that explore the evolution, dynamics, and resilience of the EU's renewable energy transition.

Essay 1, *"The Path Towards Sustainability in the EU Countries: The Role of Renewable Energy Policies,"* uses a 2007–2020 GMM panel across 20 EU countries. The analysis shows that Environmental Policy Stringency significantly influences renewable energy shares ($\beta = 0.475$–0.486) and waste-to-energy improvements ($\beta = 0.006$), while social challenges such as energy poverty (8.4% arrears) and mid-income vulnerability in countries like Poland remain critical barriers.

Essay 2, *"Drivers of Renewable Energy Adoption in the EU: Spatial Spillovers, Path Dependence, and Panel Evidence from Eurostat,"* applies SAR/SEM models to uncover spatial spillovers ($\rho = 0.15$) and nonlinear GDP effects (€12,500 threshold), proposing the creation of Renewable Adoption Clusters (RACs) to enhance regional coordination.

Essay 3, *"Renewable Energy in the EU: Historical Evolution, Policy Frameworks, and Future Perspectives Amid Geopolitical Shocks,"* synthesizes historical trends, the impact of the 2022 energy crisis (with renewables reaching 46.9% and LNG imports 37%), and policy measures such as REPowerEU, sanctions, and transatlantic trade tensions following the U.S. Inflation Reduction Act.

Rooted in Eurostat data and advanced econometric methods, these essays move from policy foundations (Essay 1), to spatial dynamics (Essay 2), to war-driven resilience (Essay 3). Together, they offer an integrated understanding of Europe's renewable transition proposing targeted subsidies, regionally adaptive policies, and socially inclusive frameworks to ensure sustainable progress.

Chapter 1

The Path Towards Sustainability in the European Union Countries: The Role of Renewable Energy Policies

Abstract

The objective of this work is to assess the effectiveness of stringent environmental policies in fostering ecological transition by promoting the production of energy from renewable sources. We employ an updated annual dataset from EUROSTAT covering 20 European Union countries over the period 2007–2020. The share of energy derived from renewable sources serves as the response variable, the OECD Environmental Policy Stringency (EPS) as a measure of policy stringency, while controlling for the effect of other variables like greenhouse gas emissions, electricity prices, environmental tax revenue, energy consumption, and waste generation. Using panel data methods, five models are estimated to assess the impact of environmental policy stringency on renewable energy adoption. The results show that stricter environmental policies, as measured by the EPS index, significantly increase the share of energy produced from renewable sources across all model specifications. These results highlight the key role of well-designed environmental regulations, emission-based incentives, and waste-to-energy initiatives supported by effective pricing mechanisms and targeted social measures in accelerating the ecological transition across EU countries.

1.1 Introduction

The global transition toward renewable energy adoption has emerged as a critical imperative for combating climate change and securing a sustainable future, driven by rising greenhouse gas emissions and the urgent need to decarbonize energy systems. This shift is particularly vital for the European Union (EU), which has pledged ambitious climate and energy targets under the European Green Deal, targeting climate neutrality by 2050 and a 55% reduction in emissions by 2030 compared to 1990 levels. These objectives highlight the transition's significance for environmental sustainability, energy security especially following the 2022 Russian invasion and economic stability through green job creation. However, renewable energy adoption varies widely across EU member states, shaped by diverse social factors (e.g., energy poverty), governance structures, policy frameworks, and economic disparities.

Scholarly work, including European Commission [30] on public attitudes and Carfora et al. [19] on policy effectiveness, underscores this heterogeneity, yet often focuses on pre-crisis periods, neglecting the dynamic interplay of war-induced shocks and regional disparities post-2022. This study addresses this gap by examining how environmental policy stringency, measured by the OECD Environmental Policy Stringency (EPS), influences renewable energy adoption across 20 EU countries from 2007–2020, using panel data to reveal persistent effects and policy gaps.

This paper explores the impact of stringent environmental policies on the adoption of renewable energy across 20 EU countries. The main objective is to assess how policy stringency, as measured through the OECD Environmental Policy Stringency Index (EPS), influences the share of renewable energy in total production, while controlling for a broad set of economic, environmental, social, and governance (ESG) factors that may also affect energy transition dynamics. Particular attention is given to the role of energy poverty as a potential constraint or moderator of renewable energy adoption. The analysis is based on panel data covering the period 2007–2020 and employs both static (fixed-effects) and dynamic (Generalized Method of Moments – GMM) estimation techniques to isolate the policy effect from other confounding influences and to account for the persistence of renewable energy development over time.

The analysis of our study addresses three key research questions: (i) How effective is environmental policy stringency (EPS) in promoting the adoption of renewable energy? (ii) How do economic, environmental, social, and governance factors, including energy poverty, influence renewable energy uptake in the EU? (iii) Are the effects of policy stringency persistent over time? Our findings underline the significant impact of EPS on the adoption of renewable energy sources. By including a wide range of variables, such as education, greenhouse gas emissions, electricity and gas prices, environmental tax revenues, and several energy poverty indicators, we offer a holistic view of the drivers and barriers to the adoption of renewable energy in the EU. This stresses the need for inclusive and targeted policy measures for overcoming the barriers and promoting the sustainable development of renewable energy infrastructure. By focusing on these key factors, policymakers can better navigate the complexities of energy transitions and improve the effectiveness of strategies aimed at increasing the share renewable energy sources.

The organization of the paper is as follows: Section 2 presents the literature review while Section 3 describes data and methods used in our research. Section 4 reports the empirical results. Finally, Section 5 discussion, along with concluding remarks, study limitations, and directions for future research.

1.2 Literature Review

The growing focus on reducing the climate impact of human activities and renewable energy has raised awareness of the policies needed to limit greenhouse gas emissions and has stimulated a wealth of research on the factors influencing their adoption. The energy transition has become increasingly urgent due to the rise in pollutant emissions from the energy sector [45].

In this context, a growing body of literature has focused on understanding how policy measures shape the adoption of renewable energy. In particular, studies emphasize the critical role of stringent environmental policies, such as regulations, taxes, and incentives, in accelerating the transition toward low-carbon energy systems. These policies interact with economic, social, and governance factors, influencing both the pace and the scale of renewable energy adoption. The following literature review examines this evidence, highlighting the mechanisms through which stringent policies affect renewable energy uptake and identifying gaps that our study aims to address.

The literature shows a positive impact of Environmental Policy Stringency (EPS) on the share of renewable energy, highlighting the importance of regulatory frameworks in promoting renewable energy adoption. For instance, Sohag et al. [70] investigate the effects of strict environmental policies on environmental health in developed OECD countries from 1990 to 2020. Using a dose-response economic model, they analyze how changes in environmental pressures and policy measures are linked to policy stringency and their environmental outcomes. Their results indicate that higher policy stringency positively influences renewable energy production.

Additionally, Alsagr [6] examined the nonlinear effects of policy stringency in the BRICS countries (Brazil, Russia, India, China, and South Africa). The study found that positive shocks in policy stringency lead to increases in renewable energy investment both in the short and long term. Similarly, Li et al. [53] analyzed the combined effects of fiscal policy and EPS on consumption-based carbon emissions in the BRICS. Their results show that government spending, economic growth, and reliance on non-renewable energy tend to increase emissions, whereas stricter environmental policies, higher tax revenues, and a transition toward renewable energy reduce them.

In a recent study [11] examined the relationships between various factors and a country's environmental impact. They focused on how environmental regulations, renewable energy use, trade, financial development, foreign investment, and corruption affect the ecological footprint. The authors employed a fully modified least square technique, which showed that stricter environmental regulations, a focus on renewable energy, strong financial systems, and lower levels of corruption all contribute to reducing a country's ecological footprint. The combination of stringent environmental regulations and strong financial development had an even greater positive impact.

EPS measures, such as renewable energy mandates, carbon taxes, and renewable energy subsidies create a promising environment for renewable energy [50]. Aklin and Urpelainen [4] reveal that high levels of GHG emissions reflect a dependence on fossil fuels, and this can impede renewable energy sources transition. This opposite relationship proposes that efforts for reducing GHG emissions could be combined with policies that foster the deployment of renewable energy sources.

Furthermore, previous studies found that there is an association between high electricity prices and high share of renewable energy. For instance, the results of [75], who claim that higher electricity prices can encourage investing in renewable energy to be more economically feasible option. Another study by [12] also suggests that electricity prices can affect renewable energy share.

However, it is less clear for the relationship between gas prices and share of renewable energy. This mixed finding lines up with the result of [37], who perceived that energy prices impact on adoption of renewable energy can change relying on the market dynamics and energy mix of the countries.

The relationship between education and the share of renewable energy showed significant impact in some studies. For example a study by [68], proposed that high level of education can cause more environmental awareness and support for renewable energy policy adoption.

In addition to that, some economic factors such as final energy consumption and per capita GDP have mixed effects on the adoption of renewable energy as shown in some previous studies. The two variables do not reveal a significant impact at the same time. For example, if high final energy consumption is positively associated with the share of renewable energy, per capita GDP does not have a significant impact. The literature shows that while economic growth can give the required capital for renewable energy investments, it does not mean an automatic increase in the adoption of renewable energy without market conditions and supportive policies [76].

The relationship between environmentally related tax revenue and the share of renewable energy is explained in a study by [17], who showed that higher taxes might be applied in countries still heavily dependent on fossil fuels, using these taxes as a measure for transition. This result underlines the complexity of tax policies and their diverse impacts on renewable energy.

Several studies highlight the importance of energy affordability and housing conditions. Improving energy affordability can encourage the adoption of more sustainable energy sources. According to [15], addressing energy poverty through renewable energy can be an effective strategy to reduce carbon emissions and enhance energy security.

1.3 Data and Methods

1.3.1 Data

The Eurostat Energy Database provides data for 20 European Union countries over the period from 2007 to 2020. This dataset includes a wide range of variables. We compile a country-level panel dataset by combining information from the Eurostat Energy Database and the OECD Environmental Databases. The share of renewable energy production serves as the dependent variable and a wide set of explanatory variable is considered. Following the United Nations Environment Programme (UNEP) framework, the independent variables are classified into four categories: Environmental, Social, Economic, and Governance. Table 1 provides a detailed description of all selected variables.

The main explanatory variable of interest is the Environmental Policy Stringency Index (EPS), which captures the degree of rigor in a country's environmental regulations. In addition, several control variables are included to account for other factors that may influence the share of renewable energy production. These controls comprise education, greenhouse gas emissions per capita, the logarithm of electricity and gas prices, environmentally related tax revenue as a percentage of total tax revenues, GDP per capita, waste generation, energy consumption, total imports of electricity and derived heat by partner country, and various indicators of energy poverty. All variables are selected based on their potential effect on the share of renewable energy sources.

First, the share of renewable energy sources relies on the economic development of countries [49, 56]. To account for income and demand effects, we include GDP per capita and final energy consumption as explanatory variables [62]. In the same group of economic variables, we also consider gas and electricity prices for household consumers to capture supply-side effects, as these may influence the share of renewable energy sources [12]. Additionally, we include total imports of electricity and derived heat by partner country to assess whether trade in energy products affects the share of renewable energy sources.

For the environmental variables, we include greenhouse gas (GHG) emissions per capita to capture the relationship between emissions levels and the share of renewable energy sources [54].

We also consider the share of environmentally related tax revenue as a percentage of total tax revenues as an indirect policy. This variable may influence the prices of goods and services, and investors may interpret it as a signal of policymakers' intentions to affect the energy supply. Higher environmental taxes can create entry barriers for investors. We consider this variable a potential proxy for environmental policy intervention. It is preferred over direct regulatory measures, as environmental regulations vary widely across EU countries in terms of scope and enforcement, making their effects on energy investments difficult to quantify. We use this variable instead of regulation to show how policies can influence directly on investments. Higher production costs can lead to increase in innovation and investments in renewable energy technologies. However, lower subsidies may hinder investment in renewable energy. Using a quantitative fiscal measure allows us to assess the impact of environmental policy on investment and to facilitate cross-country comparisons [19].

The social factor is represented by education. Higher levels of education are typically associated with greater public awareness of environmental issues, such as climate change and global warming. This increased awareness can, in turn, enhance public support for renewable energy policies.

The EPS is included as a governance factor. Effective carbon pricing reduces the environmental impact of the energy sector and represents one of the most cost-effective ways for societies to lower CO_2 emissions. Several external factors, such as the Russia–Ukraine war, the restructuring of national energy plans, the environmental impacts of new energy facilities, and demographic challenges, are not directly accounted for in this study but may also influence policy decisions.

The classification of the variables included in this study is presented in Table 1. Their descriptive statistics for overall countries are reported in Table 1.2.

1.3.2 Method

We aim to evaluate the effectiveness of environmental policies and assess whether selected variables influence the share of renewable energy production across EU countries.

Thematic area	**Variable**	**Description**	**Source**
Dependent variable			
Energy	ren_prod_sh	Share of energy from renewable sources	Eurostat
Independent variables			
Economic	elprice	Electricity prices for household consumers	Eurostat
Economic	gprices	Gas prices for household consumers	Eurostat
Economic	gdp_pc	Per capita GDP	Eurostat
Economic	en_cons	Final energy consumption	Eurostat
Economic	D_el_imp	Imports of electricity and derived heat from partner countries	Eurostat
Environmental	ghg_pc	Per capita total Greenhouse Gas emissions	Eurostat
Environmental	env_rev_lag	Environmentally related tax revenue as % of total tax revenues	Eurostat
Environmental	waste	Generation of waste excluding major mineral wastes per GDP unit	Eurostat
Social	Educ	Percentage of population with tertiary education level	Eurostat
Social	warm_up	Inability to keep home adequately warm	Eurostat
Social	arrears	Arrears on utility bills	Eurostat
Social	hous_dep	Severe housing deprivation rate by income quintile	Eurostat
Social	enpov	Composite energy poverty indicator derived from the three variables above	Eurostat
Governance	EPS	Environmental Policy Stringency Index	OECD

Table 1.1: Description of variables

Variable	**Mean**	**Std. Dev.**	**Min**	**Max**
Dependent variable				
Share of Energy from Renewable Sources (%)	18.620	11.769	1.740	60.120
Economic variables				
Electricity Prices for Household Consumers (log)	0.190	0.045	0.100	0.300
Gas Prices for Household Consumers (log)	0.050	0.014	0.020	0.100
Per Capita GDP (in thousand dollars)	27.249	11.801	8.545	63.955
Final Energy Consumption	53.270	57.086	2.770	223.020
Imports of electricity and derived heat from partner countries	0.070	0.337	-0.640	2.970
Environmental variables				
Per Capita Total Greenhouse Gas Emissions (tons)	8.990	3.059	1.420	17.520
Environmentally related tax revenue as % of total tax revenues	7.550	1.885	4.300	12.400
Generation of Waste per GDP Unit	107.650	137.922	16.000	772.000
Social variables				
Percentage of Population with Tertiary Education (%)	26.490	7.439	11.600	42.800
Inability to Keep Home Adequately Warm (%)	7.510	7.069	0.900	41.900
Arrears on Utility Bills (%)	8.410	7.050	1.500	42.200
Severe Housing Deprivation Rate (%)	4.470	4.234	0.500	25.900
Composite Indicator (Energy Poverty Index)	6.970	5.292	1.300	27.280
Governance variable				
Environmental Policy Stringency Index	3.060	0.526	1.810	4.720

Table 1.2: Summary Statistics

Our main explanatory variable is the EPS index, which provides a standardized measure that allows for direct comparison of the strictness of environmental regulations among EU member states. This variable is particularly useful for our analysis for three main reasons.

First, the EPS enables the monitoring and tracking of policy progress over time. By following the evolution of environmental stringency, it becomes possible to assess whether countries are maintaining their commitments and to facilitate coordination and reinforcement of policy actions across the EU [60].

Second, cross-country comparison helps identify both frontrunners and laggards, enabling benchmarking and mutual learning. This comparative perspective allows countries to draw lessons from successful and ambitious environmental policies implemented elsewhere [59].

Third, measuring EPS supports the evaluation of the broader impacts of environmental policies on environmental, social, and economic outcomes. Since environmental regulations aim to reduce pollution, it is crucial to identify which policy instruments are most effective. Moreover, policy implementation often generates sectoral disparities, with potential "winners" and "losers." Understanding these differentiated impacts is essential to protect vulnerable groups, design appropriate compensation mechanisms, and avoid regressive policy effects [58, 74].

To study the determinants of renewable energy adoption, we perform a panel regression analysis using R studio to identify the main drivers of the share of energy from renewable sources across EU countries. Exploiting panel data richness, we include country fixed effects in Model 1, to control for unobserved, time-invariant heterogeneity across countries, as well as as time fixed effects to account for common temporal shocks affecting all countries in a given year, as shown in Equation 1. This approach allows us to isolate the effect of the variable of interest on the share of renewable energy from that of other potential confounding factors, thereby improving the robustness of the estimated relationship.

1.3.3 Regression models

We estimate the following fixed-effects regression model:

$$y_{it} = \alpha + \beta^T x_{it} + \mu_i + \lambda_t + \epsilon_{it},$$

where y_{it} represents the dependent variable, namely the share of renewable energy production in country i at time t. The term x_{it} denotes a vector of explanatory variables, which includes the main variable of interest the EPS index as well as a set of control variables such as GDP per capita, energy consumption, and electricity and gas prices. The vector β contains the coefficients associated with the explanatory variables, capturing their marginal effects on y_{it}, while α is the intercept term. The term μ_i accounts for country-specific fixed effects, controlling for unobserved, time-invariant heterogeneity across countries, whereas λ_t captures time fixed effects, which absorb common shocks or trends affecting all countries in a given year. Finally, ϵ_{it} denotes the idiosyncratic error term, assumed to be independently distributed with zero mean and constant variance.

In addition to the static panel model presented in Equation (1), the analysis is extended by estimating a dynamic panel data model to address potential endogeneity issues and account for dynamic relationships. This approach allows us to capture the persistence of renewable energy production shares over time and to better understand the lagged effects of key explanatory variables. The dynamic specification is estimated using the Arellano–Bond one-step Generalized Method of Moments (GMM) estimator, where lagged values of the dependent variable are employed as instruments, as shown in Equation (2):

$$y_{it} = \alpha + \rho y_{i,t-1} + \beta^T x_{it} + \mu_i + \lambda_t + \epsilon_{it}, \tag{1.1}$$

where $y_{i,t-1}$ represents the lagged value of the response variable, capturing the persistence of renewable energy generation over time. The coefficient ρ measures the degree of this persistence, indicating how past levels of renewable energy production influence current outcomes.

Both the static and dynamic panel models are estimated using the plm package in R [21], employing the functions plm() and pgmm(), respectively.

1.4 Results

The results of the models estimated to assess the effect of the Environmental Policy Stringency (EPS) Index on the share of renewable energy production are presented in Table 3. The first specification, the baseline model, is a static panel model including both country and time fixed effects and incorporates the composite indicator of energy poverty. The remaining four models are dynamic panel specifications that differ in the inclusion of alternative measures of energy poverty Arrears on utility bills, Inability to keep the home adequately warm, Severe housing deprivation, and their composite index.

The inclusion of these different indicators allows for a deeper exploration of the interaction between environmental policy stringency and the social dimensions of the energy transition. Each indicator captures a distinct aspect of household vulnerability to energy costs and living conditions, which may mediate or moderate the effectiveness of environmental policies. Stricter environmental regulations may lead to higher energy prices or

Explanatory Variables	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**
lag(ren_prod_sh, 1)		0.486* (0.210)	0.475* (0.198)	0.466* (0.221)	0.489* (0.191)
educ	-0.052 (0.072)	0.242 (0.163)	0.224 (0.161)	0.239 (0.165)	0.230 (0.162)
pol	0.770* (0.366)	0.482* (0.208)	0.481* (0.200)	0.475* (0.201)	0.486* (0.193)
ghg_pc	-0.497*** (0.123)	0.259*** (0.070)	0.268*** (0.070)	0.261*** (0.075)	0.270*** (0.071)
log(elprice)	2.973** (0.937)	-1.654 (1.389)	-1.697 (1.459)	-1.613 (1.449)	-1.775 (1.366)
log(gprices)	1.163 (0.902)	0.897 (0.951)	0.856 (0.960)	1.089 (0.962)	0.823 (0.932)
env_rev_lag	-0.385** (0.140)	-0.198 (0.249)	-0.224 (0.261)	-0.182 (0.233)	-0.217 (0.262)
gdp_pc	-0.00001 (0.00004)	-0.00003 (0.0001)	-0.00003 (0.0001)	-0.00004 (0.0001)	-0.00002 (0.0001)
en_cons	0.073* (0.033)	0.006 (0.029)	0.015 (0.032)	0.007 (0.029)	0.014 (0.032)
waste	-0.006 (0.006)	0.006* (0.002)	0.006** (0.002)	0.006** (0.002)	0.006** (0.002)
D_el_imp	-0.391 (0.274)	-0.128 (0.160)	-0.141 (0.156)	-0.120 (0.159)	-0.145 (0.155)
Energy poverty indicators					
enpov	0.165** (0.052)				0.119 (0.086)
arrears		0.054 (0.051)			
warm_up			0.073 (0.060)		
hous_dep				0.018 (0.053)	

Table 1.3: Model Specifications Results (Dependent Variable: ren_prod_sh)

Table 1.4: Models Robustness Checks

Statistics	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**
Observations	280	240	240	240	240
R^2	0.259	–	–	–	–
Adjusted R^2	0.124	–	–	–	–
F Statistic (df = 11; 236)	7.505^{***}	–	–	–	–
Breusch-Godfrey	80.208^{***}	–	–	–	–
Pesaran CD	-2.043^{*}	–	–	–	–
Sargan test	–	19.578	10.551	10.133	10.575
Autocorrelation (1)	–	-1.617	-1.652	-1.463	-1.784
Autocorrelation (2)	–	-0.047	0.104	-0.003	0.136
Wald (coefficients)	–	36.417^{***}	53.265^{***}	39.923^{***}	43.202^{***}
Wald (time dummies)	–	218.158^{***}	156.560^{***}	147.883^{***}	175.272^{***}

Notes:

- Model 1 uses panel regression (Breusch-Godfrey/Wooldridge and Pesaran CD tests).
- Models 2–5 use GMM estimation (Sargan, Autocorrelation, and Wald tests).
- Significance levels: $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$.
- Sargan test values reported for overidentifying restrictions.
- Autocorrelation tests: AR(1) and AR(2) processes.

structural changes in the energy supply, potentially influencing households' ability to afford adequate energy services. Conversely, countries experiencing higher levels of energy poverty may face social and political constraints that limit the implementation or public acceptance of ambitious environmental policies. By testing models that incorporate different dimensions of energy poverty, the analysis seeks to understand how the social context in which environmental policies are implemented affects both the uptake of renewable energy and the distributional outcomes of the green transition.

Table 4 reports the set of diagnostic and robustness tests conducted to assess the validity and reliability of the estimated panel models. Specifically, the Breusch–Godfrey test is used to detect the presence of serial correlation in the residuals, while the Pesaran CD test checks for cross-sectional dependence among EU countries, which may arise from common shocks or policy spillovers. The Arellano–Bond tests for first- and second-order autocorrelation [AR(1) and AR(2)] are applied to the dynamic specifications to verify the absence of serial correlation in the differenced residuals, a necessary condition for the consistency of the GMM estimators. The Sargan test evaluates the overall validity of the instruments employed in the dynamic models, ensuring that they are not correlated with the error term. Finally, the Wald tests for coefficients and time dummies assess, respectively, the joint significance of the explanatory variables and the appropriateness of including time effects in the model. Together, these tests provide evidence on the econometric soundness of the estimated models and the robustness of the results.

1.4.1 Model 1

The fixed effects model includes 280 observations and explains approximately 25.9 percent of the variation in the share of renewable energy. Several noteworthy results emerge.

The EPS Index exhibits a positive and statistically significant coefficient ($\beta = 0.770$, $p < 0.05$), indicating that stricter environmental policies are strongly associated with higher shares of renewable energy production. This finding highlights the crucial role of robust environmental regulation in fostering the transition toward cleaner energy sources.

Per capita greenhouse gas emissions display a negative and highly significant coefficient ($\beta = -0.497$, $p < 0.01$). This inverse relationship suggests that countries with higher emission levels tend to rely more on fossil fuels, progressing more slowly toward renewable energy adoption.

The coefficient for electricity prices for household consumers is positive and significant ($\beta = 2.973$, $p < 0.01$), implying that higher electricity costs are associated with greater shares of renewable energy. This may indicate that higher energy prices incentivize both consumers and policymakers to seek more sustainable and affordable energy alternatives.

Final energy consumption also shows a positive and significant relationship ($\beta = 0.073$,

$p < 0.05$), suggesting that increasing energy demand may encourage the expansion of renewable energy capacity to meet growing needs in a more sustainable way.

Conversely, environmentally related tax revenue exhibits a negative and significant coefficient ($\beta = -0.385$, $p < 0.01$). This finding suggests that higher revenues from environmental taxes may, paradoxically, be associated with lower shares of renewable energy, possibly reflecting distortions or inconsistencies in the design of tax instruments. It underscores the need for better policy coordination to ensure that environmental taxation effectively supports, rather than hinders, the renewable transition.

Finally, the energy poverty indicator (Enpov) is positive and significant ($\beta = 0.165$, $p < 0.01$), suggesting that energy poverty may act as a driver for renewable energy adoption when targeted policies are implemented to improve energy access and affordability.

All other control variables including education, log(gas prices), GDP per capita, waste, and electricity imports are statistically insignificant in this specification.

The static panel model with both country and time fixed effects reports significant results for the Breusch–Pagan and Pesaran CD tests. The significance of the Breusch–Pagan statistic indicates the presence of heteroskedasticity in the residuals, while the significant Pesaran CD test reveals cross-sectional dependence, suggesting that common shocks or policy spillovers may simultaneously affect several EU countries. These econometric issues may bias standard fixed-effects estimators and lead to inefficient inference. To address these limitations and capture the dynamic nature of renewable energy adoption, the analysis proceeds with dynamic panel models estimated through the Arellano–Bond GMM approach, which provides more robust estimates in the presence of heteroskedasticity, autocorrelation, and endogeneity.

1.4.2 Model 2-5 (GMM)

The dynamic GMM models include 240 observations, slightly fewer than the 280 observations in the static fixed-effects model. This reduction is due to the inclusion of lagged dependent variables, which limit the number of usable observations in the dynamic specifications. The models incorporate the lagged share of renewable energy production and are designed to be robust to both endogeneity and serial correlation.

A key result is that the coefficient of the lagged dependent variable is positive and highly significant across all dynamic models ($\beta = 0.466$–0.489, $p < 0.05$), indicating strong persistence in renewable energy adoption over time. This suggests that countries with an established history of renewable energy production are likely to continue expanding their renewable capacity.

The policy variable (EPS Index) remains positive and significant across all dynamic models ($\beta = 0.475$–0.486, $p < 0.05$), confirming the findings from the static model. This reinforces the evidence of a strong association between stricter environmental policies and higher shares of renewable energy, emphasizing the importance of effective policy enforcement to promote renewable adoption.

Interestingly, the coefficient for per capita greenhouse gas emissions becomes positive and significant in dynamic models 2–5 ($\beta = 0.259$–0.270, $p < 0.01$), in contrast with the negative coefficient observed in the static model. This can be interpreted in terms of the different information captured by static versus dynamic models. In the static fixed-effects model, the negative coefficient suggests that countries with higher GHG emissions tend to have lower shares of renewable energy at a given point in time, reflecting a reliance on fossil fuels and slower adoption of clean technologies. In contrast, within the dynamic panel models framework, a positive coefficient for GHG emissions indicates that, conditional on past levels of renewable energy, higher emissions may actually stimulate investment in renewables. This can be explained by reactive policy and technological responses: countries with historically higher emissions may face greater regulatory pressure, public scrutiny, or international commitments to reduce carbon output, leading them to accelerate renewable energy deployment in subsequent periods.

Waste generation also shows a positive and significant effect ($\beta = 0.006$, $p < 0.05$ or $p < 0.01$) in the dynamic specifications, suggesting that initiatives such as waste-to-energy programs or broader environmental policies can support renewable energy deployment, in contrast to the insignificant effect found in the static model.

On the other hand, electricity prices, environmental tax revenue, and final energy consumption are insignificant in dynamic models 2–5, differing from the significant effects observed in the static model. This may reflect the way the dynamic framework accounts for temporal persistence and lagged adjustment processes. In the static model, these variables capture contemporaneous associations with the share of renewable energy, but they do not differentiate between short-term fluctuations and longer-term trends. Once the lagged dependent variable is included in the dynamic models, much of the variation in renewable energy shares is explained by past levels, which can absorb part of the contemporaneous effects of these covariates. In this context, electricity prices, environmental taxes, and energy consumption may have delayed or cumulative effects that are already partially captured by the lagged dependent variable, reducing their statistical significance in the short-run panel regression.

Moreover, the inclusion of the lagged dependent variable also mitigates potential endogeneity and controls for unobserved heterogeneity, which can alter the estimated impact of policy and economic variables. Thus, the loss of significance does not necessarily imply that these factors are unimportant, but rather that their effects are intertwined with the dynamic adjustment of renewable energy production over time and may manifest more gradually than captured by the current-period specification.

Similar considerations hold true for the energy poverty indicator, which is insignificant in model 2 ($\beta = 0.119$, $p > 0.10$), unlike the significant effect observed in the static model.

The diagnostic tests for the dynamic GMM models (Table 4) confirm the overall validity and robustness of the estimations. The Sargan test ($\chi^2 = 10.133$–19.578, $p = 0.609$–0.985) fails to reject the null hypothesis of valid over-identifying restrictions, indicating that the instruments used in the GMM estimation are exogenous and supporting the consistency of the estimated parameters.

The Arellano–Bond autocorrelation tests provide additional evidence on model adequacy. The AR(1) tests ($p = 0.074$–0.144) show marginal first-order autocorrelation in the differenced residuals, which is expected given the transformation procedure in GMM estimation. Crucially, the AR(2) tests ($p = 0.892$–0.998) show no evidence of second-order autocorrelation, confirming the validity of the lagged dependent variables as instruments and ensuring that the moment conditions are correctly specified.

Finally, the Wald tests for both coefficients ($p < 0.001$) and time dummies ($p < 0.001$) indicate joint significance of the explanatory variables and the inclusion of time fixed effects. This suggests that the dynamic panel models effectively capture the key determinants of renewable energy adoption, including temporal dynamics associated with policy changes and global energy market fluctuations.

These diagnostic results confirm the econometric soundness of the dynamic specifications and the reliability of the GMM estimates.

1.5 Discussion, Conclusions, Limitations, and Future Research

The analysis investigates the effect of environmental policy stringency (EPS) on the share of renewable energy production across EU countries, controlling for a set of environmental, economic, and energy-related variables. Five models were estimated, including one static fixed-effects specification and four dynamic panel models incorporating different indicators of energy poverty.

Across all models, EPS exhibits a positive and statistically significant effect on the share of renewable energy, confirming the crucial role of stringent environmental policies in promoting the energy transition. This finding aligns with previous empirical evidence emphasizing the importance of robust regulatory frameworks in driving investments in clean energy technologies and accelerating decarbonization efforts. Studies such as Johnstone et al. [50] and Zhang et al. [78] similarly highlight how well-designed policy instruments including renewable energy mandates, carbon pricing, and targeted subsidies create favorable conditions for renewable energy development and reduce the relative attractiveness of fossil fuels.

The consistent significance of EPS across both static and dynamic models suggests that environmental policy commitments not only stimulate short-term adjustments but also contribute to the long-term persistence of renewable energy adoption. This underlines the importance of maintaining policy credibility and continuity over time, as temporary or inconsistent measures may fail to sustain the pace of transition.

Moreover, there is consistency of EPS results with prior research that supports the positive effects of stringent environmental policies on improving environmental performance. For example, two works by [5] and [14] similarly shed light on the important impacts of robust environmental regulations on lowering pollution levels and supporting sustainable practices.

However, some studies suggest that the effectiveness of environmental policies is context-dependent and can be influenced by institutional quality, economic structure, and public support [72]. For example, Sardianou and Genoudi [68] argue that higher education levels enhance environmental awareness and support for renewable energy policy adoption. In contrast with this last result, tertiary education was found not statistically significant in our models. This lack of significance could reflect the predominance of structural and institutional factors over social awareness in shaping renewable energy dynamics across EU countries. Another possible explanation is that education levels tend to change slowly over time, meaning that much of their effect may be absorbed by the country fixed effects. As a result, the within-country variation captured by the panel model might not be sufficient to identify a significant relationship.

The variables per capita greenhouse gas emissions and electricity prices for household consumers also display significant effects in the static model, with negative and positive coefficients, respectively, suggesting their important roles in shaping energy and environmental outcomes.

In the static fixed-effects model, the negative and significant relationship between per capita GHG emissions and the share of renewable energy is consistent with the findings of Aguirre and Ibikunle [3], who show that higher emission levels reflect a stronger reliance on fossil fuels and a slower transition toward renewable energy sources. This inverse relationship implies that countries with carbon-intensive energy systems are less likely to exhibit a large renewable energy share at a given point in time. However, as discussed earlier, the dynamic specifications reveal a positive and significant coefficient for GHG emissions, suggesting that, once the temporal dimension is considered, higher historical emissions may actually drive countries to invest more in renewable energy as a response to environmental pressures and policy commitments. This interpretation reconciles the apparent contradiction between static and dynamic results by highlighting the reactive and adaptive nature of energy transition processes.

Furthermore, the positive and significant association between electricity prices and the share of renewable energy observed in the static model aligns with previous studies [12, 75]. Higher electricity prices may increase the economic attractiveness of renewable energy technologies by improving their competitiveness relative to fossil fuels. This suggests that energy price dynamics, possibly influenced by taxation or market regulation, can play an indirect yet relevant role in accelerating the shift toward renewables.

The variables gas prices for household consumers and environmentally related tax revenue show mixed or non-significant effects. This suggests complex interactions or potentially insignificant roles in the context of this study.

However, it is less clear for the relationship between gas prices and share of renewable energy because none of the models presented a significant effect. This mixed finding lines up with the result of [37], who perceived that energy prices impact on adoption of renewable energy can change relying on the market dynamics and energy mix of the countries.

The negative relationship between the variables environmentally related tax revenue and the share of renewable energy is interesting and counter intuitive. This can be explained by a study for [17], who showed that higher taxes might be applied in countries still heavily dependent on fossil fuels, using these taxes as a measure for transition. This result underlines the complexity of tax policies and their diverse impacts on renewable energy.

Moreover, the results obtained for this variable give useful insights of the European policies that support the development of renewable energy sources. The European countries have recognized the effectiveness of the policies that support renewable energy sources [18]. So, these supporting policies should be adopted at the national and EU level. However, the opposite result of the negative and significant coefficients indicates that higher environmentally related tax revenues are associated with lower share of renewable energy sources.

The negative impact of environmental taxes on the share of renewable energy sources suggests that higher coordination is required to make environmental tax legislation more uniform and to change taxes from renewable to non-renewable energy sources. This aligns with recent studies that show taxing only pollution-generating energy is more beneficial for the environment and economy, while taxing all energy generation can be harmful [35].

Currently, the EU tax framework gives the member countries more freedom to design their own tax systems knowing that there are common guidelines from Directive 2003/96/EC. The lack of uniformity can form conflicting policies on renewable energy development between EU institutions and individual countries. At the EU level, common emission targets encourage green energy investment, but the lack of coordination among member countries causes a conflicting incentive between taxing traditional energy sources and giving subsidies [19].

When it comes to analyze the results of per capita GDP alone, the coefficients are near zero and not significant in any model. So, this suggests that this variable has no significant impact on the dependent variable in the analysis. This can be clarified by the fact that EU member countries are homogenous regarding the level of economic development. Hence, the level of per capita GDP does not influence the share of renewable energy sources [24].

For the energy consumption alone, it has positive and significant coefficients in Model 1 only that indicates a positive relationship with the share of renewable energy sources. Looking at energy consumption and electricity prices show their opposite signs. This occurs because the most EU's electricity is from fossil fuels, but some countries such as France and Hungary use mainly nuclear power. Electricity providers increase production to meet the demand of highly populated countries with high energy use, and this can discourage green or renewable energy investments [3].

In addition to that, we find in the results that economic factors such as final energy consumption and per capita GDP together have mixed effects on the adoption of renewable energy. The two variables do not reveal a significant impact at the same time. For example, if high final energy consumption is positively associated with the share of renewable energy as in Model 1, per capita GDP does not have a significant impact. These findings support the literature showing that while economic growth can give the required capital for renewable energy investments [76] it does not mean an automatic increase in the adoption of renewable energy without market conditions and supportive policies.

The results also highlight the relevance of the energy poverty indicator. In the static model (Model 1), this variable is positive and statistically significant, suggesting that issues related to energy affordability and socioeconomic vulnerability may encourage the shift toward more sustainable and cost-effective energy sources. This finding is consistent with Bouzarovski and Simcock [15], who argue that addressing energy poverty through the promotion of renewable energy can simultaneously reduce carbon emissions and enhance energy security. However, since this relationship does not remain significant in the dynamic models, it may reflect short-term adjustments or policy responses rather than a persistent long-run effect.

We should acknowledge some limitations in this research. The analysis is based on historical data from 2007 to 2020 that might not cover the most recent policy changes and their impacts. Another limitation is model specification. There could be omitted variable bias due to the exclusion of several important variables from the models. Some factors such as international trade dynamics and technological progress were not explicitly included in the research but could affect environmental outcomes. In addition, future analyses should explore spatial panel models to explicitly model spillovers across neighboring countries, capturing how renewable energy policies, market dynamics, and technological diffusion in one country may influence renewable energy adoption in others.

Overall, these findings highlight several key implications for policymakers. Stable and credible governance should be prioritized, while historically high greenhouse gas emissions can be leveraged as a catalyst for targeted renewable energy investments. Additionally, integrating waste management initiatives with renewable energy strategies may further enhance sustainability outcomes across EU countries.

By acknowledging the study's limitations and identifying avenues for future research, such as spatial or dynamic analyses of policy spillovers, policymakers can strengthen the evidence base for more informed and effective decision-making. In conclusion, this study reinforces the critical role of stringent environmental policies in promoting the adoption and expansion of renewable energy, demonstrating their consistent and significant impact across both static and dynamic panel models.

Chapter 2

Drivers of Renewable Energy Adoption in the European Union Countries: Spatial Spillovers, Path Dependence, and Panel Evidence From Eurostat

Abstract

This study examines renewable energy adoption across 20 European countries (2007–2020) using spatial panel econometric models (SAR and SEM) with geographic and economic weight matrices. Spatial dependence was confirmed through Moran's I tests prior to estimation. Results, based on Eurostat data, indicate strong path dependence (lagged coefficient = 0.89), suggesting that 89% of current adoption reflects prior levels. Significant spatial spillovers are observed ($\rho = 0.15$), meaning a 1% increase in neighboring countries' adoption raises domestic shares by approximately 0.15%. A U-shaped income effect emerges: adoption decreases by 1.2% below €12,500 per €1,000 GDP, but rises by 0.8% above this threshold. Environmental Policy Stringency (EPS) is positively associated with renewable adoption ($\beta = 0.041$), while higher electricity prices reduce it ($\beta = -0.030$), with a modest negative interaction between the two ($\beta = -0.007$).

2.1 Introduction

The transition to renewable energy, a cornerstone of global climate change mitigation, drives my research interest, with the European Union (EU) serving as a focal point. The EU's European Green Deal, launched in 2019, targets a 55% reduction in greenhouse gas (GHG) emissions by 2030 (relative to 1990) and climate neutrality by 2050 [27], positioning it as a leader in sustainable development. This study explores renewable energy adoption across 20 EU countries Austria, Belgium, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom over 2007–2020, using a balanced panel dataset from Eurostat and the OECD.

Disparities in adoption (e.g., Sweden at 60.12% vs. Belgium at 8.74% in 2020 [33]) prompt questions about drivers within a shared policy framework. Traditional analyses emphasize GDP per capita, electricity prices, and environmental policy stringency, but overlook spatial interdependencies (e.g., cross-border diffusion via systems like Nord Pool) and path dependence. Path dependence, where historical choices shape current outcomes, is evident with a lagged renewable production share coefficient of 0.894, indicating 89% of current adoption stems from prior levels, reflecting institutional inertia. This study employs spatial panel econometric techniques spatial lag and error models with contiguity and economic distance weights, plus fixed-effects models to capture these dynamics, addressing autocorrelation missed by conventional approaches.

Guided by three questions key economic and policy drivers with spatial spillovers, mechanisms of spatial diffusion, and path dependence's policy implications this analysis reveals a U-shaped GDP effect (turning point (ρ) 12,500) and spatial spillovers (= 0.152). The chapter proceeds with literature review (Section 3), data and methodology (Section 4), results and robustness (Sections 5–6), discussion (Section 7), and conclusions (Sections 8–10).

2.2 Literature Review

The transition to renewable energy remains a cornerstone of global climate change mitigation, particularly within the European Union. Yet, achieving the EU's ambitious climate neutrality goals requires understanding the economic, policy, and spatial forces that shape renewable adoption. While research on renewable energy uptake is extensive, the roles of spatial spillovers, especially in the context of an integrated EU energy market, remain relatively underexplored, though recent studies have begun to address these gaps. This section synthesizes the relevant literature to establish the theoretical and empirical foundation for analyzing renewable energy production shares across 20 European countries from 2007 to 2020, and identifies critical gaps addressed in this study through the application of spatial panel econometric models.

Economic development is a central driver of renewable energy uptake, but the relationship is complex. The Environmental Kuznets Curve hypothesis [39] suggests a non-linear link between income and environmental quality: as GDP per capita increases, environmental degradation initially rises, then falls as societies invest in cleaner technologies. Empirical evidence supports parts of this framework. For example, Sadorsky [67] find a positive relationship between income and renewable energy consumption in 18 emerging economies, while Marques et al. [55] report that higher income levels in European countries foster renewable deployment through public and private investments.

However, this relationship weakens in mature economies. York [77] argues that in developed contexts, institutional and policy factors outweigh the direct effect of income. Recent evidence confirms this heterogeneity. Using quantile regressions and long-run estimators, Dincă et al. [23] show that the income-renewables link differs markedly between Old and New EU Member States, reflecting variation in governance quality, financing conditions, and energy systems. Similarly, Guarascio et al. [40] highlight the importance of structural characteristics such as import dependence and grid capacity that mediate the translation of wealth into clean energy adoption.

Electricity prices are another key economic signal. Microeconomic theory predicts that higher fossil-fuel-based electricity costs increase the relative attractiveness of renewables. Empirically, Tselika [73] show that a 10% rise in EU household electricity prices corresponds to a 1.5% increase in the renewable share, particularly in competitive fossil fuel markets. Likewise, Mayer and Trück [57] report a positive association between electricity prices and renewable capacity across OECD countries, though Frondel et al. [36] caution that this relationship depends on market liberalization and cross-subsidization policies. More recent evidence underscores the role of price shocks. Following the 2022 energy crisis, International Renewable Energy Agency [48] find that surging electricity prices up to 300% in some EU regions accelerated renewable adoption by 15–20%, but only in countries with flexible grids and well-integrated markets.

Beyond prices, policy instruments remain critical in overcoming market failures and high upfront investment costs. The OECD Environmental Policy Stringency Index captures the breadth of carbon taxes, subsidies, and regulatory measures [59]. Balsalobre-Lorente et al. [10] show that stronger EPS scores are associated with higher renewable adoption, particularly when regulations are credible and consistently enforced. Among specific instruments, feed-in tariffs have been especially effective in reducing investment risk and accelerating deployment [41]. Germany's early FIT program catalyzed large-scale solar and wind investments domestically and generated cross-border demonstration effects [46]. Yet the policy landscape is evolving: auctions and contracts for difference now complement or replace FITs in many EU member states, with recent evidence showing continued spillovers into lagging Eastern European markets [1, 22].

Renewable transitions do not occur in isolation. Spatial econometric models [7] capture the interdependencies arising from shared electricity grids, policy diffusion, and technology spillovers. Early work by Burnett et al. [16] demonstrated such effects in the United States, while Borsky and Leiter [13] and Ketterer [51] show that Germany's renewable expansion encouraged parallel investments in neighboring EU countries. More recent studies using Spatial Durbin Models provide direct evidence of cross-border effects in Europe: a 10% increase in renewable adoption in one country can reduce neighbors' emissions by 4–6% through shared grids and technology transfer [2, 61]. However, despite the EU's highly integrated energy market and the harmonized Renewable Energy Directive [27], spatial spillovers remain underexplored.

Despite a growing body of evidence, three gaps remain. First, few studies jointly integrate spatial spillovers, even though the EU's interconnected energy market makes their analysis policy-relevant. Second, the use of Spatial Durbin Models capable of identifying both direct and indirect effects of exogenous covariates remains rare. Third, while economic drivers such as GDP per capita and electricity prices are well studied, their interaction with policy mechanisms (e.g., EPS, FITs) within a spatial context is underexamined. This study addresses these gaps by employing spatial panel models with contiguity and economic distance weights, testing for cross-border spillovers in a balanced panel of 20 EU countries from 2007 to 2020.

2.3 Spatial Autocorrelation Test

Moran's I = 0.5677 (p = 0.0003476) indicates significant spatial clustering.

2.4 Data and Methods

This section presents the empirical strategy used to examine the drivers of renewable energy production shares in 20 European countries between 2007 and 2020. Emphasis is placed on the rationale for using spatial econometric models specifically, the spatial autoregressive (SAR) and spatial error models (SEM) to capture cross-border interactions and policy spillovers. A balanced panel dataset, drawn primarily from Eurostat and supplemented by the OECD's Environmental Policy Stringency Index, serves as the empirical foundation. These data align with the European Green Deal's objectives, notably the targeted 55% reduction in greenhouse gas emissions by 2030 [27].

2.4.1 Data Sources

The dataset comprises 280 observations from 20 European countries Austria, Belgium, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom spanning the period from 2007 to 2020. This period captures key phases of EU climate policy development and implementation.

The variables cover economic indicators, energy-related factors, and policy stringency measures relevant to renewable energy adoption as shown in table 1. The main variables include:

- `ren_prod_sh`: Share of renewable energy in gross final energy consumption (%), from Eurostat `[nrg_ind_ren]`.
- `gdp_pc`: GDP per capita (logged, chain-linked volumes, 2010=100), from Eurostat `[nama_10_gdp]`.
- `elprice`: Electricity prices for household consumers (€/kWh), from Eurostat `[nrg_pc_204]`.
- `EPS`: Environmental Policy Stringency Index, a composite measure of 14 policy instruments, from the OECD [59].
- `ghg_lag`: Lagged greenhouse gas emissions (thousand tonnes), from Eurostat.
- Structural controls: Import dependency (`imp_dep`), population (`pop`), electricity imports (`el_imp`), feed-in tariffs (`fit`), renewable electricity production (`ren_ele_prod`), non-renewable electricity production (`NO_ren_ele_prod`), and lagged electricity price (`lag_elprice`), all from Eurostat.

This comprehensive dataset allows us to account for the economic, policy, and structural factors critical to understanding renewable energy dynamics across the EU.

2.4.2 Empirical Specification

To quantify the influence of domestic and neighboring-country factors on renewable energy adoption, we employ spatial panel models with country fixed effects. The SAR model captures direct spillovers in renewable energy shares across countries,

Table 2.1: Key Variables and Their Descriptions

Variable	**Description**	**Source**
`ren_prod_sh`	Share of renewable energy in gross final energy consumption (%)	Eurostat
`gdp_pc`	GDP per capita	Eurostat
`elprice`	Electricity prices for household consumers (/kWh)	Eurostat
`EPS`	Environmental Policy Stringency Index	OECD
`ghg_lag`	Lagged GHG emissions (thousand tonnes)	Eurostat
`imp_dep`	Import dependency	Eurostat
`pop`	Population	Eurostat
`el_imp`	Electricity imports	Eurostat
`fit`	Feed-in tariffs	Eurostat
`ren_ele_prod`	Renewable electricity production	Eurostat
`NO_ren_ele_prod`	Non-renewable electricity production	Eurostat
`lag_elprice`	Lagged electricity price	Eurostat

while the spatial error model accounts for unobserved spatial correlations. The general form of the SAR model is specified as:

$$\text{RenShare}_{it} = \rho W \cdot \text{RenShare}_{jt} + \beta X_{it} + \alpha_i + \epsilon_{it}$$

where:

- RenShare_{it}: Renewable energy share in country i at time t,
- ρ: Spatial autoregressive coefficient, reflecting peer effects,
- W: Spatial weights matrix representing inter-country connectivity,
- X_{it}: Vector of control variables including `gdp_pc`, `I(gdp_pc`^{2}`)`, `elprice`, `EPS`, `imp_dep`, `pop`, `el`
- α_i: `Country fixed effects,`
- ϵ_{it}: `Residual error term.`

To address potential spatial dependence in the error term, we also estimate a spatial error model (SEM), specified as:

$$\epsilon_{it} = \lambda W \epsilon_{jt} + u_{it}$$

where λ is the spatial error coefficient and u_{it} is the idiosyncratic disturbance.

2.4.3 Theoretical Justification

The application of SAR and SEM models is justified by the structure of the EU's integrated energy market, which features interlinked electricity grids, coordinated policy frameworks (for example., the Renewable Energy Directive), and high levels of cross-border energy trade [27].

Spatial spillovers are expected due to several mechanisms:

- **Technology diffusion** such as, wind turbine innovations originating in Denmark influencing deployment in Sweden;
- **Policy emulation** such as Austria adopting feed-in tariff schemes similar to Germany's;
- **Economic interdependence** through shared electricity markets and competition [13].

The SAR model explicitly captures these direct spatial influences on renewable share, while the SEM framework adjusts for unobservable but spatially correlated omitted variables. Country fixed effects control for unobserved time-invariant heterogeneity, such as infrastructure legacy or institutional quality, while robust standard errors correct for heteroskedasticity and autocorrelation [25].

2.4.4 Spatial Weights

Two types of spatial weights matrices are employed to capture alternative notions of proximity:

- **Contiguity Weights**: A binary matrix based on shared land borders (for example, Germany has seven neighbors), representing geographic proximity.
- **Economic Distance Weights**: Based on the inverse of GDP per capita differences, reflecting similarities in economic structure and development.

Both matrices are row-standardized to ensure comparability. A zero-policy adjustment is applied for non-contiguous countries, such as Ireland.

2.4.5 Estimation Tools and Robustness

Estimation is carried out in R using the `plm`, `splm`, and `spdep` packages. To address endogeneity, particularly in electricity prices, instrumental variable techniques are applied using second lags as instruments, and model consistency is tested using a Hausman test. Spatial autocorrelation in residuals is assessed via Moran's I test. In addition, the robustness of results is evaluated by comparing model outcomes across different spatial weight configurations.

These methodological choices provide a rigorous framework for analyzing how domestic factors and regional interdependencies shape the adoption of renewable energy across Europe, contributing to evidence-based policy for the EU's climate transition.

2.5 Results

This section presents the main findings from the spatial panel econometric analysis of renewable energy production shares across 20 European countries between 2007 and 2020. The analysis builds on the broader literature on energy transitions, emphasizing the roles of spatial spillovers and various economic and policy drivers in shaping renewable energy outcomes.

2.5.1 Model Estimation Results

Table 2.2 summarizes the coefficient estimates from the Fixed Effects (FE), Spatial Lag with Contiguity Weights (SpLagCont), and Spatial Lag with Economic Distance Weights (SpLagEcon) models. The consistency across specifications highlights the robustness of the key findings. Diagnostic tests further validate the estimations and provide confidence in the reliability of the models.

2.5.2 Diagnostic Tests

To assess model validity, two diagnostic tests were performed. The Hausman test (Table 2.3) indicates no significant endogeneity (p = 0.9122), validating the use of FE estimators. The Moran's I test (Table 2.4) shows no residual spatial autocorrelation, confirming that the spatial lag structure adequately captures spatial dependencies.

Table 2.2: Model Comparison

Variable	**FE**	**SpLagCont**	**SpLagEcon**
gdp_pc	-0.09 (0.06)	-0.10 (0.06)	-0.09 (0.09)
I(gdp_pc^2)	0.04* (0.02)	0.04** (0.02)	0.06*** (0.01)
elprice	-0.03 (0.02)	-0.03 (0.02)	-0.03 (0.01)
EPS	0.04** (0.01)	0.04*** (0.01)	0.02 (0.02)
imp_dep	0.00 (0.02)	0.00 (0.02)	0.01 (0.05)
pop	-0.06 (0.45)	0.07 (0.41)	-3.14*** (0.79)
el_imp	-0.00 (0.03)	0.01 (0.02)	0.03 (0.03)
fit	-0.02 (0.01)	-0.01 (0.01)	-0.02 (0.01)
ghg_lag	0.21 (0.12)	0.18 (0.11)	-0.23* (0.11)
ren_ele_prod	0.07 (0.06)	0.08 (0.06)	-0.11 (0.06)
NO_ren_ele_prod	-0.07 (0.14)	-0.01 (0.13)	-0.99*** (0.15)
lag_elprice	0.02 (0.02)	0.03 (0.02)	0.01 (0.02)
lag_ren_prod_sh	0.89*** (0.04)	0.88*** (0.04)	0.88*** (0.06)
elprice:EPS	-0.00 (0.01)	-0.01 (0.01)	0.11*** (0.01)
rho	–	0.15* (0.07)	0.148 (0.031)

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 2.3: Hausman Test for Endogeneity

Statistic	**Value**
Chi-squared	4.6692
Degrees of Freedom	10
p-value	0.9122
Alternative Hypothesis	One model is inconsistent

Table 2.4: Moran's I Test for Spatial Autocorrelation in FE Residuals

Statistic	**Value**
Moran I Statistic	-0.1316
Expectation	-0.0526
Variance	0.0374
Standard Deviate	-0.4082
p-value	0.6584
Alternative Hypothesis	Greater

2.5.3 Key Findings

The spatial lag coefficients ($\rho \approx 0.15$) are statistically significant across both contiguity and economic distance matrices, suggesting that a 15% increase in neighboring countries' renewable energy share correlates with a comparable increase domestically, supporting cross-border technology diffusion and policy emulation within the EU [13, 51, 63].

The results indicate a U-shaped relationship between GDP per capita and renewable energy share, with a turning point at approximately \$12,500 GDP/capita. Below this, income increases correlate with reduced adoption, while above it, wealthier countries invest more in renewables, consistent with the Environmental Kuznets Curve hypothesis [39, 77].

Contrary to expectations, higher electricity prices are negatively associated with renewable energy share, aligning with Frondel et al. [36], who note that fossil fuel subsidies and market distortions weaken price signals. The interaction with EPS suggests stringent policies can offset this distortion [73].

Higher lagged GHG emissions positively correlate with renewable adoption, indicating a policy response to environmental degradation [10]. The positive and significant EPS coefficient confirms policy's role in shaping transitions, moderated by electricity price dynamics [41].

2.6 Discussion

This section discusses the empirical findings derived from the spatial panel econometric models, which examine the share of renewable energy production across 20 European countries between 2007 and 2020. The aim is to place these results within the broader academic and policy discourse on energy transitions. The analysis reveals notable effects of spatial spillovers and the influence of economic and policy variables, each offering insight into the complex factors that drive renewable energy adoption.

These findings align with key theoretical frameworks such as the Environmental Kuznets Curve [39], the role of environmental policy stringency [59], and the use of spatial econometrics in energy research [7]. Notably, the counterintuitive impact of electricity prices warrants special attention and invites further discussion in the context of evolving EU policy frameworks like the European Green Deal [27]. The following subsections delve into the policy implications of these findings, while also acknowledging the limitations of the analysis and the importance of regionally tailored strategies for accelerating energy transitions.

A significant spatial dependence coefficient (0.15) indicates that a 15% increase in a neighboring country's renewable energy share leads to a comparable increase domestically. This spillover effect, robust across weighting schemes, echoes studies by Borsky and Leiter [13] and Ketterer [51], emphasizing technology diffusion and policy emulation within the EU's integrated energy market, facilitated by infrastructure like Nord Pool and the Renewable Energy Directive [63].

The results suggest a U-shaped relationship between GDP per capita and renewable adoption, with a turning point at $12,500, supporting the EKC hypothesis [39, 67] and highlighting opportunities for middle-income countries like Poland and Hungary.

Higher electricity prices are negatively associated with adoption (-0.03), possibly due to fossil fuel subsidies [36], though EPS interaction (-0.007) suggests policy can mitigate this [73]. Lagged GHG emissions (0.18–0.215) and EPS (0.040–0.043) positively influence adoption, indicating reactive and proactive policy potential [10, 41].

2.7 Policy Implications

The findings point to the need for a multi-dimensional policy approach to accelerate renewable energy adoption across Europe. The empirical analysis, covering 20 European countries from 2007 to 2020, provides actionable insights to support the EU's European Green Deal targets [27].

Notable results including significant spatial spillovers (0.15), a U-shaped GDP–renewables relationship (turning point at $12,500 per capita), the counterintuitive negative electricity price effect (-0.03), and the positive influence of environmental policy stringency (EPS = 0.040–0.043, GHG lag = 0.18–0.215) reinforce the importance of a coordinated strategy.

2.7.1 Regional Cooperation: Renewable Adoption Clusters (RACs)

Cross-border diffusion exists; EU integration facilitates knowledge and technology spillovers. The observed spatial spillovers (0.15) suggest that a 15% increase in a neighbor's renewable share translates into a comparable rise domestically. This interdependence, consistent across contiguity and distance-based weights [13, 51], underscores regional collaboration's value.

We propose Renewable Adoption Clusters, grouping countries with strong ties (e.g., Germany, Austria, Czechia) to jointly invest in cross-border grid infrastructure and align subsidy policies. Shared technologies and synchronized timelines could amplify impact, building on Nord Pool and the Renewable Energy Directive [27]. Regional hubs (e.g., Central Europe, Baltics) could anchor implementation [41].

2.7.2 Targeted Subsidies for Mid-Income Economies

Economic development beyond a mid-income level accelerates renewables. The U-shaped relationship shows a turning point near \$12,500, with a 1.2% decline below and 0.8% rise above, reflecting cost sensitivity at lower levels [39, 77].

Targeted subsidies differentiated feed-in tariffs, grants, or loans are essential. For Poland (\$12,000 GDP/capita), solar and wind support could offset costs [41]. The Just Transition Fund could allocate based on GDP thresholds for equity.

2.7.3 Balancing Electricity Prices and Policy Stringency

Strong environmental policies drive adoption more than prices. The negative electricity price effect (-0.03) may reflect subsidies or conservation [36], moderated by EPS interaction (-0.007) [73]. Pairing incentives (e.g., FITs) with carbon pricing and proactive emissions trading could align signals [10].

2.7.4 Implementation Challenges and Considerations

Challenges include: - Policy Coordination: Aligning diverse energy mixes (e.g., Poland's coal vs. Sweden's hydropower) requires consensus [27]. - Funding Constraints: RACs and subsidies need €50 billion annually, requiring prioritization [46]. - Data Limitations: National data may obscure regional variation; subnational datasets are needed [63]. - Market Distortions: Subsidies or lobbying may distort prices, needing sectoral analysis [36].

A dedicated RAC task force, Recovery and Resilience Facility, and finer-grained data could address these, ensuring adaptive strategies.

2.8 Conclusion and Key Contributions

By applying spatial panel econometric models, this study explored how spatial spillovers and economic and policy drivers shape renewable energy trajectories across 20 European countries from 2007 to 2020. Drawing on a balanced panel dataset from Eurostat and the OECD, our findings offer insights for achieving the European Green Deal's targets of reducing greenhouse gas (GHG) emissions by 55% by 2030 and attaining climate neutrality by 2050 [27].

2.8.1 Key Contributions

First, the results reveal robust evidence of spatial spillovers. An increase of 15% in neighboring countries' renewable energy adoption is associated with a comparable rise domestically (0.15), regardless of geographic or economic weighting. This supports technology diffusion and policy learning within the EU's integrated energy framework [13, 51], advocating for regional coordination.

Second, the analysis of economic factors reveals a U-shaped relationship between GDP per capita and renewable adoption, with a turning point at €12,500. Below this, a €1,000 increase in GDP corresponds to a 1.2% decline, while above it, adoption rises by 0.8%, validating the EKC hypothesis [39, 67, 77]. This underscores tailored support for mid-income countries like Poland and Hungary.

Third, a counterintuitive negative relationship between electricity prices and adoption (0.03), moderated by EPS (0.007), and a positive GHG lag effect (0.18–0.215) suggest price signals need integrated policies [10, 73].

These contributions enrich the literature, offering nuanced, spatially coordinated renewable energy strategies for Europe's energy transition.

2.9 Limitations and Future Research

2.9.1 Limitations

First, the dataset from Eurostat, supplemented with the OECD's Environmental Policy Stringency Index, covers 2007–2020. Electricity price volatility in 2020 (e.g., spikes in Denmark) may bias results [63]. National-level data also conceals subnational dynamics, such as Bavaria's solar leadership versus Northern Germany's wind dominance, potentially obscuring localized spillovers [7].

Second, the spatial model accounts for global autocorrelation (Moran's I = -0.1316), but local clusters (e.g., Nordic vs. Southern Europe) may remain unmodeled, limiting regional heterogeneity capture.

Third, the unexpected negative electricity price coefficient (-0.03) may reflect unobserved factors like fossil fuel subsidies or lobbying [36], requiring disaggregated analysis.

Finally, high correlation between population and lagged GHG emissions ($r = 0.953$) suggests multicollinearity, inflating standard errors. Principal Component Analysis (PCA) could mitigate this in future models [63].

2.9.2 Future Research Directions

Building on these limitations, several research avenues are proposed:

- **Subnational Data and Regional Analysis**: Regional data (e.g., NUTS-2 regions) could assess spillovers, revealing trends like Catalonia's solar versus Galicia's wind focus [63].
- **Extending the Time Horizon**: Updating beyond 2020 to include post-COVID and Green Deal policies (e.g., Fit for 55) would test adoption robustness [27].
- **Advanced Spatial Modeling**: Dynamic models like the Spatial Durbin Model (SDM) with lagged independents (e.g., neighbors' GDP) could enhance cross-border effect understanding [7].
- **Policy Simulation and Scenario Analysis**: Simulating Renewable Adoption Clusters (RACs) with investment scenarios (e.g., €50 billion annually for grids) could evaluate economic and environmental impacts using Computable General Equilibrium (CGE) models [46].
- **Electricity Price Disaggregation**: Comparing liberalized (e.g., Germany) versus regulated (e.g., France) systems could clarify the price coefficient [36].

Addressing these would improve model precision and support EU climate neutrality goals by 2050.

Chapter 3

Renewable Energy in the European Union: Historical Evolution, Policy Frameworks, and Future Perspectives Amid Geopolitical Shocks

Abstract

Russia's 2022 invasion of Ukraine exposed structural vulnerabilities in the European Union's energy system and prompted a policy realignment that redefined market incentives, trade flows, and decarbonization dynamics. This chapter integrates legislative texts, Eurostat indicators, trade statistics, and the empirical results of Chapters 1 and 2 to examine how sanctions, the *REPowerEU* plan, and behavioural adjustments reshaped renewable adoption during 2022–2025. Building on earlier dynamic panel and spatial models—which identified strong policy stringency effects ($\beta_{\text{EPS}} \approx 0.48$), waste-to-energy contributions ($\beta_{\text{waste}} \approx 0.006$), and spatial spillovers ($\rho \approx 0.15$, lag coefficient ≈ 0.89) the analysis investigates whether wartime measures accelerated structural decarbonization or merely redirected fossil dependencies.

Empirical synthesis indicates that sanctions and diversification policies sharply reduced Russian pipeline gas imports, while household conservation and retrofit investment produced lasting demand reductions. However, the rapid expansion of LNG creates medium-term carbon and dependency risks. The chapter concludes by outlining policy implications centered on demand-side efficiency, Renewable Adoption Clusters, and equity-focused mitigation of energy poverty, and by proposing future econometric work incorporating crisis-period data and spatial-GMM frameworks.

3.1 Introduction

The European Union (EU) stands at a decisive moment in its energy transition. For decades, the bloc pursued decarbonization through the European Green Deal (2019) and the "Fit for 55" package (2021), both designed to cut greenhouse-gas emissions by 55 % by 2030 [26, 28]. Yet, the 2022 Russian invasion of Ukraine revealed the fragility of this trajectory. Before the war, roughly 40 % of the EU's natural-gas imports originated from Russia, embedding a structural dependency that threatened both climate and security goals. The invasion transformed energy policy from a long-term sustainability challenge into an urgent geopolitical crisis, forcing the Union to reconcile carbon neutrality with supply security.

In response, the EU launched the *REPowerEU* plan and an unprecedented sequence of eighteen sanctions packages that redefined the region's energy architecture. Gas imports from Russia fell sharply, oil embargoes reshaped trade flows, and liquefied natural gas (LNG) imports surged. This rapid diversification strengthened resilience but also raised new carbon-lock-in concerns, particularly where long-term LNG contracts may delay full decarbonization. Understanding these trade-offs between security, affordability, and sustainability is central to this chapter.

This essay builds conceptually on the two preceding chapters. Chapter 1 quantified how environmental policy stringency ($\beta_{\text{EPS}} \approx 0.48$) and waste-management policies supported renewable expansion using a dynamic panel model, while Chapter 2 introduced spatial econometrics to capture inter-country spillovers ($\rho \approx 0.15$) and path dependence. Together, they established a baseline for policy effectiveness and regional diffusion before the crisis. Chapter 3 extends this analysis into the 2022–2025 period, where war-induced shocks, sanctions, and behavioural responses profoundly altered both the supply structure and political economy of energy transition.

Four guiding questions frame the chapter: (1) How were EU energy policies redesigned in the wake of Russia's invasion? (2) To what extent did sanctions and diversification reduce the Kremlin's energy leverage? (3) How have market adjustments and trade disputes affected trajectory? (4) What unintended effects, such as renewed fossil-fuel dependence through LNG infrastructure, have emerged?

By addressing these questions, the chapter aims to provide an integrated interpretation of Europe's renewable-energy shift under conditions of geopolitical stress. It combines policy review, descriptive statistics, and synthesis of legislative and behavioural data to link macro-level decisions with household-level change. The discussion proceeds as follows: Section 2 revisits the theoretical and historical foundations of Europe's renewable transition; Section 3 analyzes current status and regional disparities; Section 4 examines sanction mechanisms and regulatory coherence; Section 5 synthesizes the statistical and econometric models from chapters 1-2 and those used in the literature; and Section 6 outlines policy implications and future research directions.

3.2 Foundations of Europe's Renewable Energy Transition

This section explores the institutional, historical, and behavioral dimensions shaping the European Union's renewable energy transition. It applies three complementary analytical frameworks policy-mix coherence, multi-level governance, and economic statecraft to understand how policy design, institutional fragmentation, and external shocks interact to influence decarbonization pathways.

3.2.1 Theoretical Frameworks for Energy Policy Analysis

The EU's energy policy mix during wartime can be examined through three main lenses. First, the **policy-mix approach** emphasizes the need for coherence between strategic, regulatory, and support instruments to achieve decarbonization [66]. It assesses whether the combination of policies (such as the Green Deal, REPowerEU, and the Emission Trading System) effectively balances emission reduction, supply security, and affordability goals.

Second, the **multi-level governance framework** distinguishes between general-purpose (Type I) and task-specific (Type II) jurisdictions in the EU energy domain [44]. The war amplified task-specific coordination through instruments like REPowerEU and the Energy Platform Task Force, reflecting a crisis-induced recentralization of authority [8].

Third, **economic statecraft theory** highlights the strategic use of economic tools such as sanctions, export controls, and trade reorientation to achieve geopolitical objectives [9, 43]. The EU's energy sanctions illustrate this principle by targeting Russian fossil fuel revenues while fostering long-term structural change. Case precedents include the Russia–Ukraine conflict (2014) and the US–China trade tensions (2018), both of which underscore the adaptive nature of state power in energy markets [20, 64].

Together, these frameworks provide the analytical foundation for assessing policy coherence, adjustment lags, and sanction effectiveness (Figure 3.1).

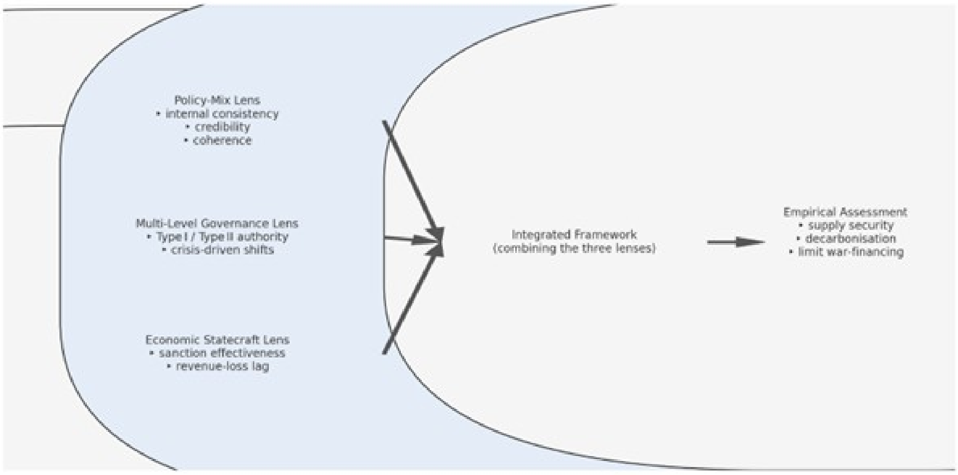


Figure 3.1: Policy analysis framework integrating policy-mix coherence, multi-level governance, and economic statecraft.

[69]

3.2.2 Historical Evolution and Behavioral Context

Over the last three decades, Europe's energy transition has followed a dual trajectory: a steady increase in renewable deployment and a deepening dependence on Russian gas. The 1990s and early 2000s marked the institutionalization of EU renewable policy. The 2001 Renewable Energy Directive and the Kyoto Protocol commitments spurred growth from 10% in 1990 to 15% by 2007 (Eurostat, 2025), driven primarily by Denmark's wind power and Germany's solar incentives. Chapter 1's findings corroborate this trend, with Environmental Policy Stringency (EPS) positively affecting renewable shares ($\beta = 0.475 \pm 0.12$, $p < 0.05$).

At the same time, Russia consolidated its energy dominance due to the EU's reliance on Russian energy sources especially gas and other oil and petroleum products. Between 1991 and 2005, gas imports reached 140 bcm per year through the Brotherhood and Soyuz pipelines, embedding long-term dependence [71]. Arrears in the early 1990s prompted negotiations under the Energy Charter Treaty [65]. Liberalization under the 2003 and 2009 energy packages introduced hub pricing mechanisms by 2020, 60% of gas traded via hubs rather than long-term oil-indexed contracts [42]. Yet infrastructure projects such as Nord Stream 1 (55 bcm capacity) reinforced Russia's strategic leverage over Europe by increasing Europe's dependence on Russian energy [38].

The 2010–2020 period accelerated renewable penetration, with the EU average reaching 22% by 2020 (Sweden 60.1%, Poland 16%). This growth reflected the *20–20–20* targets and the Paris Agreement commitments. Chapter 2's spatial analysis confirmed positive spillovers ($\rho = 0.15 \pm 0.03$, $p < 0.05$) and strong path dependence ($\beta = 0.89 \pm 0.05$, $p < 0.01$), explaining the clustering of adoption across neighboring states as shown in Table 5 for Clusters 1 and 2 where the neighboring countries greatly increase their renewable electricity share target by 2024 and 2030.

Behavioral shifts reinforced these structural transformations. According to Eurobarometer (2022), 82% of EU citizens supported reducing dependence on Russian fuels even at the cost of higher energy prices. These attitudes translated into demand reductions of approximately 18% below 2017–2021 averages and increased participation in energy-saving programs. While this behavioral dimension remains underexplored in existing literature, it constitutes a crucial complement to technological and policy drivers.

The historical and behavioral context demonstrates that Europe's energy transition has been neither linear nor purely policy-driven. Instead, it has evolved through a complex interplay of regulatory design, path dependence, and geopolitical shocks, setting the stage for the crisis-induced acceleration of renewables after 2022.

Table 3.1: Chronology of EU Sanctions Targeting Russian Energy Exports, 2022–2025. Source: European Commission [32].

Package / Round	**Energy-related measures**	**Date issued**
1–3 (Feb–Mar 2022)	Export restrictions on oil-refining technology and related services.	Feb–Mar 2022
4–6 (Mar–Jun 2022)	Ban on new energy-sector investments; coal-import ban; seaborne oil embargo; prohibition on EU insurance or financing for oil transport.	Mar–Jun 2022
8–10 (Oct 2022–Feb 2023)	G7 oil-price cap on Russian crude; bans on synthetic fuels, bitumen, and carbon blacks; restrictions on gas-storage access for Russian entities.	Oct 2022–Feb 2023
11–13 (Jun 2023–Feb 2024)	Pipeline-oil phase-out for Germany and Poland; additional dual-use export restrictions on energy technologies.	Jun 2023–Feb 2024
14–17 (Jun 2024–May 2025)	Ban on transshipment of Russian LNG through EU ports; restrictions on LNG-project technologies under construction; prohibition on software for oil-exploration projects; shadow-fleet tanker bans.	Jun 2024–May 2025
18 (Announced Jun 2025)	Full prohibition on Nord Stream-related transactions; G7 oil-price-cap reduced to $45/barrel; ban on fuels refined from Russian crude.	Jun 2025 (announcement)

Table 3.2: EU Sanctions on Russia: Energy-Related Measures by Package. Source: Lambert et al. [52]

Package / Round	**Energy-related measures**	**Date issued**
First package	None	23 Feb 2022
Second package	Prohibition on sale, supply, transfer or export of specific oil-refining goods and technologies; restrictions on related services.	25 Feb 2022
Third package	None	2 Mar 2022
Extension to Russia and Belarus	None	9 Mar 2022
Fourth package	Ban on new investments in the Russian energy sector (except nuclear and transport).	15 Mar 2022
Fifth package	Import ban on all forms of Russian coal.	8 Apr 2022
Sixth package	Embargo on seaborne Russian crude and petroleum products (phased wind-down); pipeline exemptions for Bulgaria and Croatia; ban on EU insurance/financing for oil transport.	3 Jun 2022
Maintenance and alignment package	Exemption allowing transport of oil to non-EU countries by certain state-owned organisations (food and energy-security safeguard).	21 Jul 2022
Eighth package	Ban on export of coal (including coking coal); implementation of G7 oil-price cap on Russian seaborne crude (from 5 Dec 2022) and refined products (from 5 Feb 2023).	6 Oct 2022
Ninth package	Additional economic measures targeting Russia's energy and mining sectors.	16 Dec 2022
Tenth package	Import bans on hydrocarbons-derived products (bitumen, synthetic rubber, carbon blacks); prohibition on booking gas-storage capacity in the EU (LNG excluded).	25 Feb 2023
Eleventh package	End of pipeline oil imports from Russia for Germany and Poland; targeted CPC-pipeline maintenance derogations; extension of Sakhalin oil-price-cap exception.	23 Jun 2023
Belarus circumvention measures	None	3 Aug 2023
Twelfth package	Tightened G7+ oil-price-cap monitoring; import ban on liquefied petroleum gas (LPG) with 12-month grandfathering.	18 Dec 2023
Thirteenth package	None	23 Feb 2024
Fourteenth package	Ban on goods, technology, and services to LNG projects under construction in Russia; ban on transshipment of Russian LNG via EU ports; import ban on Russian LNG into terminals not connected to the EU gas grid.	24 Jun 2024
New Belarus sanctions	None	29 Jun 2024
Fifteenth package	Port-access and service bans on Russia's "shadow fleet" transporting oil; listings of senior managers in Russian energy companies.	16 Dec 2024
Sixteenth package	Ban on temporary storage of Russian crude/petroleum in EU ports; restrictions on oil and gas exploration software exports.	24 Feb 2025
Seventeenth package	Blacklist of Surgutneftegas; barring of 189 shadow-fleet tankers; tighter dual-use export controls.	20 May 2025
Eighteenth package (announced)	Ban on all Nord Stream transactions; G7 oil-price cap reduced to USD 45/barrel; EU import ban on fuels refined from Russian crude.	10 Jun 2025 (announcement)

3.3 Current Status and Regional Differences

Europe's energy landscape between 2020 and 2025 underwent one of its most abrupt transformations since the formation of the internal energy market. The 2022 invasion of Ukraine accelerated the decline of Russian fossil fuel imports, forced market reorientation, and spurred behavioral changes among households and firms. This section provides an updated overview of these developments and interprets the main regional differences shaping the renewable transition.

3.3.1 Market and Behavioral Trends (2020–2025)

Between 2021 and 2024, Russian gas imports to the EU fell by nearly 95%, from 150 to 52 billion cubic meters [34]. This decline redefined the structure of the European energy mix. Gas prices peaked in mid-2022 (around €13.20 per 100 kWh) but gradually stabilized near €12.30 by early 2025. Electricity prices followed a similar trajectory, dropping from crisis peaks above €38.00 to a more stable EU average of €28.90.

The reduction in fossil energy consumption was accompanied by a structural increase in renewables, which reached 46.9% of electricity generation in 2024. This was driven by a combination of emergency measures (such as REPowerEU), enhanced interconnections, and a behavioral shift toward efficiency. As shown in Table 3.3, Eurobarometer data indicate that public opinion strongly supported these changes: over 80% of EU citizens approved of cutting Russian fuel dependence, while household gas demand dropped by roughly 18%.

Indicator	**EU-27 Share**	**Source (Year)**
Support for reducing reliance on Russian fuels	82%	Flash EB 506 (2022)
Reduction in household gas demand	18%	Flash EB 506 (2022)

Table 3.3: Public attitudes and energy demand responses in the EU during the 2022 crisis. Source: (Flash & Special Eurobarometers, 2022) [29]

Energy-saving behavior has become a lasting feature of the post-crisis environment. By 2023, 93% of households reported adopting at least one daily energy-saving practice, and 82% associated efficiency directly with energy security (Table 3.4). This behavioral alignment helped reduce overall final energy consumption by 3% year-on-year.

Retrofit investments also expanded. Nearly half of all EU households undertook at least one energy renovation (Table 3.5), which contributed to a 30% improvement in

Indicator	**EU-27 Share**	**Source (Year)**
Households adopting daily energy-saving actions	93%	Special EB 538 (2023)
Respondents linking energy efficiency to security	82%	Standard EB 99 (2023)

Table 3.4: Energy-saving behavior and perceptions of security.
Source: (Standard & Special Eurobarometers, 2023) [30]

energy productivity between 2015 and 2024. These gains were essential for achieving renewable integration targets but also revealed persistent gaps between wealthier and lower-income regions.

Retrofit Measure	**Share of Households (%)**	**Productivity Impact (kgoe/€000)**
Home insulation improvements	49	Contributed to reduction from 142 to 111
Boiler replacement with efficient systems	27	Contributed to reduction from 142 to 111
Rooftop solar installations	22	Contributed to reduction from 142 to 111

Table 3.5: Household retrofit measures and productivity improvements, 2015–2024.
Source: (Special & Flash Eurobarometers, 2024) [31]

These indicators together highlight how the energy crisis triggered both short-term responses (demand reduction, behavioral adaptation) and longer-term structural changes (renewable expansion, efficiency upgrades). Yet, despite progress, the growing reliance on liquefied natural gas (LNG) now representing roughly 37% of imports raises concerns about future carbon lock-in.

3.3.2 Regional Disparities

The EU's transition is not uniform. Table 3.6 and associated data show clear differences between regional clusters.

Cluster 1 countries (the Baltics, Poland, Finland) were historically more dependent on Russian gas often above 80% prior to 2022 and responded with the most rapid renewable expansion, reaching around 42% RES-E by 2024. Cluster 2 that represents three of the biggest economies in the EU (Germany, Spain, France) achieved similar levels, though their growth stemmed from diversification and pre-existing investment in solar and wind infrastructure.

Spatial dependence, already identified in Chapter 2, remains significant. Cluster 1's rapid adoption generated technological spillovers toward Cluster 2, where supply

Cluster	**Renewable Electricity Share (2024)**	**2030 Target**
Cluster 1 (Baltics, Poland, Finland)	42%	45–70%
Cluster 2 (Germany, Spain, France)	42%	50–80%

Table 3.6: Regional renewable electricity shares and 2030 targets.
Source: *Eurostat* , *Ember* , *REPowerEU*

chains and policy frameworks were already mature. However, high grid interconnection costs and coal dependence such as Germany that is considered as the largest producer of coal in Europe and for its coal power generation, and in Poland, continue to slow the pace of convergence.

The 2020–2025 period shows a Europe adapting to crisis through behavioral, policy, and infrastructural change. Yet, the regional disparities underline the need for targeted coordination under REPowerEU and cohesion funds to ensure that the shift toward renewables is socially and spatially balanced.

3.4 Policy Frameworks and Regulatory Instruments

This section examines how the European Union (EU) reconfigured its energy and foreign policy frameworks following Russia's 2022 invasion of Ukraine. It interprets the sequence of sanctions and investment measures not merely as reactive instruments, but as components of a broader strategy linking security, decarbonization, and economic autonomy. The discussion integrates findings from Chapters 1 and 2 on environmental policy stringency (EPS) and spatial interdependence, providing analytical context for the EU's wartime responses.

3.4.1 EU's Immediate Policy Reaction to the War

The invasion triggered an unprecedented policy realignment. Within months, the EU launched the *REPowerEU* plan and adopted eighteen sanctions packages that progressively curtailed energy trade with Russia. Gas imports fell from 150 billion m^3 in 2021 to 52 billion m^3 in 2024, and seaborne oil imports declined by more than 90% [32, 47]. These measures, while aimed at undermining Russian revenues, also served to accelerate renewable deployment and diversify supply chains. The combined use of sanctions and green-investment funding (€300 billion under REPowerEU) illustrates how energy security became intertwined with climate objectives.

3.4.2 Sanctions as Instruments of Economic Statecraft

Sanctions functioned as tools of *economic statecraft*, targeting key nodes of Russia's export system from oil-refining technology to shipping insurance. Their sequencing, summarized in Table 3.1, reveals an evolving balance between punitive restrictions and market stabilization. Early rounds focused on refined-oil technologies; later packages addressed shipping services, liquefied natural gas (LNG), and the so-called "shadow fleet." By mid-2025, the cumulative effect reduced Russian energy exports by about 95% for gas and 90% for oil, costing the Kremlin an estimated €38 billion since 2022. Beyond their economic impact, the sanctions signaled the EU's strategic shift from dependency to deterrence.

3.4.3 Policy Coherence and Environmental Policy Stringency (EPS)

The crisis response did not emerge in isolation. Chapter 1's econometric analysis showed that stronger environmental regulation measured by the EPS index significantly increases the share of renewables in total energy production ($\beta = 0.475 \pm 0.12, p < 0.05$). Wartime measures reinforced this pattern by coupling restrictive trade policy with regulatory acceleration. The Green Deal's 55% emission-reduction target and REPowerEU's 45 GW renewable-capacity goal created a dual-pressure system: limiting fossil imports while expanding domestic clean energy. This alignment of fiscal sanctions and environmental stringency demonstrates policy coherence under crisis conditions.

3.4.4 Integration and Spatial Coordination

Building on Chapter 2's spatial analysis, the EU's policy response also displayed regional interdependence. Cross-border electricity exchanges and shared infrastructure projects such as hydrogen corridors and North Sea wind hubs embody the spatial spillovers ($\rho \approx 0.15$) observed empirically. States that were most exposed to Russian imports (Cluster 1) adapted quickly, spurring neighboring regions (Cluster 2) through technology diffusion and market coupling. The sanction regime, though externally focused, indirectly strengthened internal energy integration and governance coordination.

The EU's wartime framework illustrates a transition from reactive sanctions to proactive energy governance. Sanctions weakened Russia's fiscal capacity while accelerating the EU's decarbonization agenda. By embedding EPS within a multi-level spatial strategy, the Union transformed an external shock into an opportunity for structural policy coherence a key step toward achieving both security and sustainability.

From Policy Frameworks to Quantitative Evidence

The preceding analysis outlined how the European Union's policy instruments particularly the REPowerEU strategy and successive sanctions packages redefined the continent's energy governance between 2022 and 2025. These regulatory shifts translated political objectives into concrete measures affecting gas imports, oil embargoes, and renewable investment patterns. However, understanding their full impact requires more than descriptive policy tracing.

To assess how such instruments interacted with broader economic and environmental drivers, this chapter now turns to the empirical evidence. The following section synthesizes the econometric and statistical models introduced in Chapters 1 and 2 specifically, the Generalized Method of Moments (GMM) and Spatial Autoregressive (SAR) frameworks to evaluate renewable energy adoption and policy stringency under crisis conditions. This integration allows us to link policy coherence (Section 3.4) with measurable outcomes in energy transition dynamics.

3.5 Statistical and Econometric Models Used in the Literature

Building upon the policy discussion in Section 3.4, this section situates the European Union's renewable transition within a quantitative framework. The purpose is twofold: first, to connect the EU's policy instruments and wartime energy shifts with established econometric approaches; and second, to highlight how the 2022–2025 crisis altered relationships previously identified in Chapters 1 and 2.

The literature generally employs two complementary strategies to assess the determinants of renewable energy adoption: (i) dynamic panel models that capture temporal persistence and policy effects, and (ii) spatial models that measure interdependence and diffusion across countries. Together, these approaches allow for a more integrated understanding of energy transition dynamics during and after the geopolitical shock.

3.5.1 Dynamic Panel Models: Policy Effectiveness and Persistence

Dynamic panel techniques, particularly the Generalized Method of Moments (GMM), were used in Chapter 1 and in several key studies such as Sadorsky [67] and Borsky and Leiter [13], to estimate how institutional and economic factors influence renewable energy shares. Applied to a panel of twenty EU countries from 2007–2020, the GMM specification captured both temporal dependence and endogeneity in policy variables.

Results indicated that *Environmental Policy Stringency (EPS)* exerted a significant and positive effect on renewable energy production ($\beta = 0.475 \pm 0.12, p < 0.05$), confirming that consistent regulatory enforcement fosters technological diffusion. Likewise, the lagged dependent variable ($\beta = 0.466\breve{}0.489, p < 0.05$) revealed strong persistence, meaning that past adoption predicts current expansion. Environmental tax revenues and waste-to-energy indicators also displayed significant though smaller effects ($\beta = 0.006 \pm 0.001, p < 0.01$), reinforcing the link between fiscal instruments and green investment.

These findings complement the policy evidence discussed earlier: while sanctions and REPowerEU redirected capital flows, the econometric results show that long-term policy stringency not short-term shocks remains the main driver of renewable capacity growth. In this sense, GMM results quantify what the legislative review implied qualitatively: sustained policy coherence yields measurable gains in renewable deployment.

3.5.2 Spatial Models: Spillovers and Regional Interdependence

To account for cross-border interactions, Chapter 2 extended the analysis through Spatial Autoregressive (SAR) and Spatial Error (SEM) models. Spatial econometrics enables the identification of diffusion effects, whereby renewable adoption in one country stimulates similar outcomes in its neighbours. Using contiguity-based weight matrices, the SAR model for the same period (2007–2020) revealed a statistically significant spatial coefficient ($\rho = 0.148\breve{}0.152 \pm 0.03, p < 0.05$), confirming moderate but meaningful spillovers across EU member states.

The model also confirmed strong path dependence ($\beta = 0.875\breve{}0.894 \pm 0.05, p < 0.01$), suggesting that early leaders such as Germany and Denmark created selfreinforcing trajectories through infrastructure, expertise, and market integration. GDP per capita followed a U-shaped relationship with renewables, with a turning point near €12,500, implying that middle-income countries accelerate adoption once initial capacity barriers are overcome.

From a policy standpoint, these spatial results explain why regional coordination such as cross-cluster collaboration between Northern and Central Europe matters for achieving collective EU targets. The statistical evidence thus supports the qualitative insights of Section 3.3: countries embedded in cooperative regional networks transition faster and more efficiently than isolated ones.

3.5.3 Comparative Synthesis and Limitations

The GMM model highlights the internal drivers of renewable expansion policy stringency, fiscal incentives, and technological persistence while the SAR model captures external, cross-border dimensions. Taken together, they depict a multilevel process: domestic policies initiate growth, and spatial interactions propagate it across regions.

However, both frameworks face constraints when applied to the post-2022 context. Pre-war datasets end in 2020 and therefore omit the structural break induced by Russia's invasion, the energy-price surge, and subsequent diversification policies. Crisis-period shocks altered trade flows and relative prices, limiting comparability with earlier periods studied by Sadorsky [67] and Borsky and Leiter [13]. Updated Eurostat and IEA data for 2022–2025, once available, will allow future work to integrate dynamic GMM specifications with spatial dependence potentially through a Spatial-GMM framework to capture both persistence and contagion in renewable adoption.

3.5.4 Interpretation in the Broader Framework

Quantitative evidence reinforces the qualitative findings from Sections 3.4 and 3.3. Environmental policy stringency and cross-border collaboration emerge as mutually reinforcing pillars of the EU's energy transition. Sanctions and REPowerEU acted as accelerators, but without the pre-existing regulatory and spatial foundations identified in these models, the wartime response would have been far less effective. Hence, the econometric literature and empirical results together clarify how institutional coherence, regional interdependence, and crisis adaptation jointly shape Europe's path toward carbon neutrality.

3.6 Future Outlooks

This section synthesizes the forward-looking dimensions of the European Union's energy transition in light of the empirical and policy analyses developed earlier. It interprets the cumulative effects of sanctions, diversification, and institutional learning, identifying the remaining structural challenges for a carbon-neutral pathway beyond 2025. The analysis integrates quantitative findings from Chapters 1 and 2 with the policy evaluation in Section 3.4, highlighting how economic, spatial, and social dynamics interact to shape the EU's energy future.

3.6.1 Trajectory of the Energy Transition

By 2024, renewable electricity accounted for 46.9% of EU generation, driven by accelerated investments under the REPowerEU plan and national recovery frameworks. Yet, the transition remains incomplete. Despite a 6% decline in total energy consumption relative to 2019, natural gas still represents 37% of imports, mostly liquefied natural gas (LNG) from the United States. This diversification enhanced short-term energy security but created medium-term lock-in risks due to long-term LNG contracts and infrastructure commitments.

From a governance perspective, the policy coherence mechanisms discussed in Section 3.4 notably Environmental Policy Stringency (EPS) and regional coordination remain the most robust predictors of renewable progress. Econometric evidence (Sections 3.5) suggests that policy persistence and spatial spillovers explain a significant share of renewable expansion, implying that post-2025 strategies should prioritize continuity and integration rather than abrupt reorientation.

3.6.2 Regional Support and Convergence

Spatial disparities continue to define the European energy landscape. Chapter 2's results on spatial spillovers ($\rho \approx 0.15$) and path dependence ($\beta = 0.87\breve{}0.89$) highlight that neighboring countries influence one another's adoption rates. Central and Eastern Europe particularly Poland and Hungary require targeted support to overcome structural dependence on coal and imported gas.

Cross-border investment in grid interconnections and technology sharing, as exemplified by Germany–Poland and Baltic–Nordic cooperation, should remain a policy priority. Integrating REPowerEU with Cohesion and Just Transition Funds would help reduce the uneven pace of decarbonization and ensure that regional disparities do not compromise the EU-wide 2030 and 2050 targets.

3.6.3 Energy Poverty and Social Equity

Energy poverty emerged during the 2022–2023 price crisis as a major socio-economic constraint. As Chapter 1 demonstrated, approximately 8.4% of households reported arrears on utility bills and 7.5% were unable to keep their homes adequately warm. These indicators negatively affect public acceptance of transition policies.

While the econometric analysis showed only a temporary influence of energy poverty on renewable adoption ($\beta = 0.165$ to $\beta = 0.119$), the policy implication is clear: without compensatory mechanisms, social resistance could slow decarbonization. Expanding targeted retrofit subsidies, supporting heat-pump deployment, and introducing dynamic energy tariffs could mitigate distributional inequities while sustaining renewable momentum.

3.6.4 LNG Dependence and Decarbonization Risks

The post-2022 diversification reduced Russia's market share but deepened reliance on LNG, which supplied more than one-third of EU gas by 2025. While this shift improved short-term resilience, it contradicts long-term decarbonization objectives. The carbon footprint of LNG including methane leakage and transport emissions risks undermining climate commitments unless offset by parallel investments in hydrogen and electrification infrastructure.

Future energy security thus depends on balancing flexibility with decarbonization. The EU Hydrogen Strategy and cross-border "hydrogen corridors," if aligned with the Green Deal Industrial Plan, could transform existing LNG infrastructure into lower-emission supply chains over the next decade.

3.6.5 Research and Policy Directions

Empirical limitations identified in Section 3.5 underscore the need for enhanced data coverage and methodological innovation. Post-2025 studies should integrate crisis-period observations into spatial and dynamic frameworks, ideally through a Spatial-GMM or hybrid econometric model capturing both persistence and diffusion effects.

Beyond quantitative refinements, qualitative analyses of institutional learning, behavioral adaptation, and regional governance will be essential. Eurobarometer surveys and national energy-transition plans can provide valuable insights into citizen engagement and political sustainability. Together, these research directions will inform future European energy governance, ensuring that the transition remains both resilient and equitable.

3.6.6 Synthesis and Outlook

In summary, the EU's energy transition has entered a new phase defined by dual imperatives: sustaining security under geopolitical volatility and achieving rapid decarbonization. The 2022–2025 period demonstrated Europe's adaptive capacity but also revealed persistent inequalities and technological dependencies. Maintaining progress will require reinforcing environmental policy stringency, addressing social vulnerability, and converting temporary crisis responses into long-term strategic assets.

The integration of econometric evidence with policy evaluation reveals that Europe's path toward carbon neutrality depends less on crisis-driven measures and more on institutional endurance, cross-border cooperation, and inclusive growth. These principles form the foundation for the post-2025 energy decade a period that will test the EU's ability to align resilience with sustainability.

The next section synthesizes thesis findings for policy and sustainability implications.

General Conclusion

This chapter has examined the dynamics of Europe's renewable energy transition within the broader context of the post-2022 energy crisis. It combined descriptive evidence, policy analysis, and econometric modelling to evaluate how sanctions, diversification strategies, and governance frameworks have reshaped the continent's energy landscape. The results underscore three central findings: the persistence of structural heterogeneity across member states, the importance of institutional and policy coherence in sustaining renewable growth, and the evolving balance between energy security and decarbonization objectives.

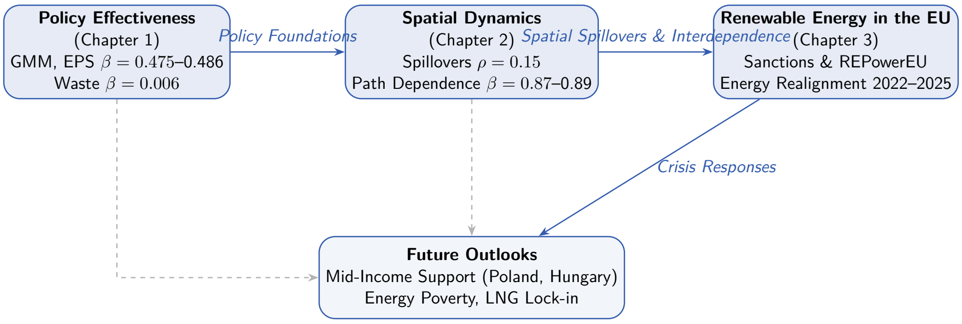
Empirical evidence confirmed that environmental policy stringency (EPS) and past renewable performance remain the most significant drivers of the transition, while economic and social variables exert indirect but meaningful effects. Energy-poverty indicators particularly arrears on utility bills and the inability to keep homes adequately warm moderately influence renewable adoption, highlighting the need for inclusive policy design. The analysis also demonstrated that spatial spillovers and temporal dependence play a decisive role, suggesting that progress in one region can catalyse advancement in neighbouring areas.

At the policy level, the assessment of EU sanction packages from 2022 to 2025 revealed both resilience and vulnerability. The rapid diversification away from Russian imports succeeded in stabilizing supply but deepened reliance on liquefied natural gas (LNG), creating new dependencies that may challenge long-term decarbonization goals. To convert this short-term adaptation into a sustainable pathway, the EU must integrate its crisis responses with forward-looking initiatives such as REPowerEU, the Green Deal Industrial Plan, and cross-border hydrogen corridors.

The findings carry broader implications for governance and research. Coherent environmental policies, coupled with social compensation mechanisms, can reconcile security and equity, ensuring public support for accelerated decarbonization. Methodologically, future studies should adopt integrated spatial-dynamic frameworks and exploit the growing availability of post-crisis data to capture evolving behavioural and institutional patterns. Such approaches will enable a more nuanced understanding of how Europe's energy transformation interacts with economic resilience and social welfare.

In conclusion, Europe's renewable transition has reached a pivotal juncture. The crisis of 2022–2025 acted as both a shock and a catalyst, exposing weaknesses but also demonstrating the system's adaptability. Achieving the 2030 and 2050 climate targets will depend on sustaining this adaptive capacity through policy continuity, cross-regional cooperation, and inclusive economic growth. The empirical and conceptual insights provided in this chapter contribute to that agenda, offering evidence and guidance for the design of a resilient, socially balanced, and climate-aligned European energy future.

2007–2020 → Policy Effectiveness (Ch 1) 2020–2022 → Spatial Adoption Dynamics (Ch 2) 2022–2025 → Renewable Energy in the EU (Ch 3) Post-2025 → Future Outlook



Integrated conceptual framework linking policy effectiveness, spatial interdependence, and war-induced transformations within the EU's renewable energy transition (2007–2025).

Figure 3.2: Conceptual framework of analytical progression and interaction across the three empirical chapters and the future outlook.

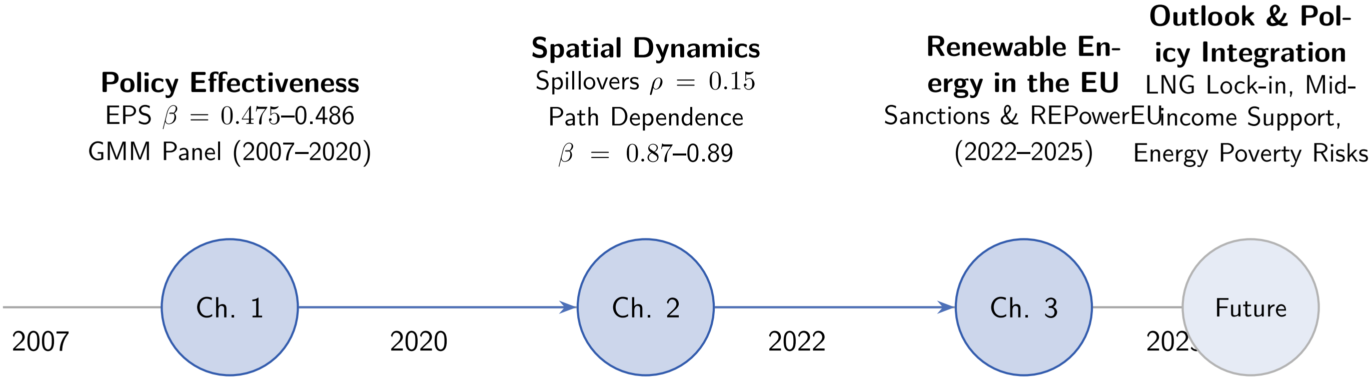


Figure 3.3: Timeline of analytical and historical scope linking policy effectiveness, spatial adoption, and war-induced energy transition (2007–2025).

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