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Electricity Production and Sustainable Development: The Role of Renewable Energy Sources and Specific Socioeconomic Factors

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Abstract: An eco-friendly and sustainable power production system constitutes the cornerstone of every country's strategic plan to tackle climate change and enhance energy resource autonomy. Carbon dioxide abatement in electricity generation, in addition to being a necessary condition for t "green" energy transition, can contribute greatly to cleaner industrial production and sustainable development. Emphasizing this key role of the power sector, the present research focuses on shedding light on the impact of renewable energy resources (RES), per capita gross domestic product (GDP), electricity gross fixed capital formation (GFCF) and urbanization in the CO_2 intensity, and the sustainability level of electricity production. The analysis is based on a comprehensive dataset of 31 countries including 26 European countries, U.S.A., Japan, Australia, Canada, and New Zealand from 1995 until 2018. The econometric outcomes revealed the strong statistical significance of all variables and a plethora of causality relationships, upon which several policy suggestions are made. Interestingly, GDP per capita beyond a certain level can gradually become an aggravating factor for the electricity carbon footprint. Similarly, the vital role of RES in clean electricity production was confirmed as expected, yet surprisingly, this effect also appears to reverse after a certain percentage of total RES reliance. In contrast to urbanization, the electricity GFCF parameter is estimated to have an adverse effect on electricity CO_2 intensity, indicating that the vast amount of new investments in the power sector concerns carbon-intensive technologies. Finally, a dynamic analysis is carried out, revealing to policy makers the necessary time frame after which the implementation of new energy policies can have the full impact on the carbon emissions of electricity generation.

Keywords: electricity production; RES; sustainable development; CO_2 abatement; environment; energy policy

JEL Classification: D40; Q30; Q40; Q43; Q48; Q50; Q58

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1. Introduction

The high level of industrialization of the world's economy during the past three centuries has led to a dramatic concentration of Greenhouse Gases (GHG) in the earth's atmosphere. The extensive use of fossil fuel combustion to cover the necessary energy needs for industrial production, households, and transportation was the main contributor to this worrying development. The phenomenon of global warming, which is triggered by excessive CO_2 emissions, is held responsible for the continuous occurrence of devastating environmental catastrophes, such as extended wildfires, deadly floods, polar zone defrosting, and sea level rise.

The energy sector creates approximately 40% of the global CO_2 volume every year with a significant part of it concerning electricity production [1]. Growing economic activity and high available income are typically combined with rising electricity demands and carbon emissions. The realization of the imminent environmental and humanitarian crisis mobilized the United Nations (UN) to develop a strategic plan, which included several initiatives that would deal with this uprising threat. In 2015m the UN endorsed 17 sustainable development goals, aiming to balance economic growth with social rights and environmental sustainability [2]. This set of goals emphasizes the importance of tackling climate change by promoting "green" electricity through RES usage and innovation.

The European Union (EU) was by far the protagonist in the implementation of CO_2 mitigation policies and RES integration into electricity generation [3]. The European Commission established an energy policy that sets stringent and compulsory targets with respect to "green" energy transition. This strategy is based upon two pillars: The decisive decrease in carbon emissions and the containment of the EU's external energy dependency, in this way, ensuring both economic and environmental sustainability [4].

Natural gas as a relatively clean fossil fuel may provide a valuable solution towards a more smooth and sequential displacement of high-polluting energy inputs such as coal until the complete switch to renewable electricity [5]. Nonetheless, the recent escalating geopolitical tension in Eastern Europe and the triggered energy crisis highlighted, in a characteristic way, the energy supply risks that threaten industrial production, households, and future economic prospects. Hence, it has become more important than ever for central governments to make substantial progress at a brisk pace towards energy autonomy. Combining electricity supply security with environmental awareness constitutes a critical challenge for all modern societies and is often associated with high economic and social costs [6]. On the other hand, designing a sustainable power system with limited carbon emissions can also offer significant opportunities and synergies. Eco-friendly electricity production technologies such as RES improve energy resource self-sufficiency and secure economic activity and growth. The gradual integration of RES into the power grid is expected to give rise to an entirely new industry, creating numerous new jobs and income. Moreover, according to [7], efficient policy making and monitoring of specific socioeconomics can moderate electricity demand, allowing further participation of RES in electricity production.

Clean and sustainable power generation constitutes the fundamental cornerstone for a successful governmental energy policy that is able to ensure continuous economic growth and environmental upgrading. Considering the key role of RES, GDP per capita, GFCF, and urbanization in the self-sufficiency and decarbonization of the power sector, the current study utilizes appropriate panel econometric techniques to investigate the dynamic effect of these crucial parameters. Based on the econometric outcomes, several amendments and new policy suggestions are proposed, which intend to guide central governments towards a sustainable electricity future.

The present work is rather innovative, contributing to academia in a number of ways. To the best of the authors' knowledge, this is the first time that an electricity-based CO_2 intensity variable is utilized, being defined as the ratio of total electricity sector CO_2 emissions (metric tonnes) to net total electricity generation (GWh). The analysis is also innovative on the grounds that the GFCF variable is isolated from other general investment-capital indices commonly used in academia and refers exclusively to the net effect of the annual capital investments in the power industry. The final novelty concerns the examination of the impact of both linear and squared GDP per capita and RES on electricity CO_2 intensity. For both variables, a U-shape relationship was confirmed with the relative turning points being estimated.

Overall, the paper is organized as follows: Sections 1 and 2 consist of the introduction to the research topic and the literature review. Section 3 presents the processed dataset, the model parameters, diagnostic tests, and methodology. Section 4 contains detailed commentary on the econometric analysis and outcomes. In Section 5, a complete summary of the most valuable economic and environmental conclusions and a series of potential policy implications are presented. Lastly, Section 6 summarizes the main findings and contributions of the paper.

2. State of the Art

2.1. GDP Contribution on CO_2 Emissions

Historical evidence shows that industrial production is almost inseparably linked to increasing GHG emissions and a high environmental burden. During the initial economic phase of rapid and simultaneous growth of GDP and air pollution, developing economies steadily create better living standards for their citizens. This essential upgrade comes at the high cost of environmental degradation, yet the basic development stage follows a decisive turning point at which environmental quality becomes progressively more important for societies.

The Environmental Kuznets Curve (EKC) proposed by [8] essentially shows, at all times, the equilibrium between GDP growth and environmental damage, depending on a country's stage of economic progress and level of total wealth. One of the first studies focusing on the subject is the work of [9], which set the fundamentals for the studies that followed. Specifically, these researchers [9], with the use of the panel data econometric methodology, investigated whether the EKC is verified by the relationship between GDP growth and sulphur emissions, also estimating the relative turning point for an extensive sample of 71 countries. In more recent years, a large group of researchers primarily focuses on carbon emissions. The vast majority of academic literature, as provided by the reviews of [10] and [11], has tested the EKC hypothesis between economic growth and environmental degradation, while ref. [12] tested the EKC hypothesis validity in the case of CO_2 emissions for 161 countries globally.

2.2. The Role of Urbanization in Energy Consumption and CO_2 Emissions

2.2.1. Urbanization and Energy Consumption Nexus

The constantly rising GHG emissions as a consequence of the excessive demand for energy drew the attention of numerous researchers to the effect of urbanization. References [13,14] support the idea that the growing level of urbanization is one of the main drivers of the intense increase in energy consumption. Interestingly, ref. [15] argues in favor of a bidirectional connection between the two variables for many countries. Other studies focus on the potentially direct association of urbanization with electricity consumption. Reference [16] concluded that solely urbanization can affect electricity demand in a positive and statistically significant way, while ref. [17] claims that the two factors interact with each other, forming a bidirectional relationship.

2.2.2. Urbanization and CO_2 Emissions Nexus

Another stimulating research topic concerns the level of environmental degradation resulting from the urbanization process. The fact that the CO_2 concentration in the atmosphere goes hand in hand with the percentage of the urban population poses a great threat and challenge for both state authorities and international organizations. Econometric outcomes from the vast majority of relative research show clear evidence that urbanization and CO_2 emissions are connected through a strong and statistically significant bidirectional effect. Reference [18] alleges that the increasing level of urbanization critically contributed to the rising carbon emissions in China and in UAE, while refs. [19,20] confirm this outcome for ASEAN, MENA, and European countries. Consistent with previous studies, authors [21] utilizing an extended dataset containing observations from 114 countries found that urbanization constitutes an increasing factor of CO_2 emissions. The study of [22] on 29 OECD countries not only complies with the previous findings but further claims that the relationship between urbanization and CO_2 is of quadratic form and is best described by an inverted U-shape curve similar to that defined by EKC. A rather interesting finding of [13,23] is that this verified influence of urbanization on energy consumption and CO_2 production can differ significantly from one geographic area to another. In contrast, studies such as that of [24–26] argue that, for certain countries, the total contribution of urbanization to the increase in carbon emissions is of minor importance.

2.3. RES Electricity Production and CO_2 Emissions

The environmental footprint of the gradual incorporation of renewable energy technologies has become one of the hottest topics in academia, with numerous scientific papers trying to provide guidance to governments and policy makers for efficient strategic energy planning.

The rise in electricity consumption triggers a notable increase in carbon emissions as reported by [27], yet renewable energy usage can moderate environmental degradation as a result of electricity generation. Investigating the influence of RES on CO_2 emissions in top renewable energy consuming countries, refs. [28,29] revealed the highly beneficial effect of RES on air pollution. This mainstream view is expressed by a plethora of relative studies, which embrace the ecologically beneficial role of RES and endorse them as a competent way to moderate the rising trend in CO_2 levels. refs. [20,30–32] highlight the contribution of RES power production in enhancing the level of the ecological quality in the European region. Likewise, refs. [33–35] confirm the positive contribution of RES energy consumption in CO_2 abatement for a high number of OECD countries, while refs. [36–38] report similar results for various developing countries and BRICST, respectively. Conversely, a certain group of researchers [39,40] opposes the aforementioned notion by presenting evidence from country-specific cases where RES deployment was related to a negligible or even negative environmental effect.

2.4. The Impact of Capital Investments on Electricity Consumption and CO_2 Emissions

The last parameter included in the research refers to the power sector's GFCF. Theoretically, financial development is expected to improve ecological quality when capital investments are driven towards R&D and RES deployment. Nonetheless, several empirical studies provided a strong indication of the negative effect of financial development on environmental downgrades. Among others, refs. [41,42] specify foreign direct investments (FDIs) as one of the main determinants of a country's energy consumption and the rise of carbon emissions. Likewise, according to [43–45], both financial development and GFCF affect the level of total energy demand; they are also responsible for directly raising CO_2 emissions. In addition, ref. [46] supports the existence of an inverted U-shape relationship between the variables. Finally, refs. [47,48] claim that the effect of capital investments on carbon emissions is relatively insignificant.

3. Methodology and Data

3.1. Data Summary

The current study attempts to shed light on the way per capita GDP [49], urbanization [50], power sector GFCF [51], and the percentage of RES usage [52] influence the amount of CO_2 that is emitted per GWh of electricity generated [53–55]. The dataset consists of observations for 31 countries with the highest GDP globally, including 26 European countries, U.S.A., Japan, Australia, Canada, and New Zealand for the time period between 1995 and 2018. The data for all sampled countries were obtained from World Development Indicators of the World Bank, the OECD statistical library, the U.S. Energy Information Administration, and the International Energy Agency.

In Table 1, the basic descriptive statistics of the total panel dataset are presented. The information of the descriptive statistics indicates that the sample is mainly composed of developed industrialized countries, with high levels of income and urbanization. The median urban population in the examined countries lies approximately at 75% of the total population, while the average annual per capita income exceeds 25.000 USD. The average environmental cost per GWh of electricity generated is estimated at approximately 519.98 metric tonnes of CO_2, with a relatively high standard deviation of 329.26 tonnes. The range for electricity CO_2 intensity varies from absolute zero to 1821.60 tonnes. This fact shows that there are countries within the sample that rely solely on RES, while at the same time, others cover domestic demand by heavily relying on obsolete technologies, such as coal-fired power plants. In line with previous findings, the renewables and electricity GFCF parameters also have a minimum of zero; however, they can vary up to 99% of the total fuel mix and 6.31% of the national GDP, respectively. These details reveal that within the sample, countries that invest from approximately zero to several billion USD in innovative RES technologies coexist. Lastly, in harmony with the values for both skewness and kurtosis, the null hypothesis of the Jarque–Bera normality test is clearly rejected for all variables, indicating the non-normality of their unconditional distribution.

Table 1. Descriptive statistics of total panel (Years: 1995–2018).

	Electricity CO_2 Intensity (1) (Metric Tons per GWh)	GDP per Capita (2) (Current USD)	Electricity GFCF (3) (% GDP)	Urbanization (4) (% Total Population)	Renewables (5) (% Total Fuel Mix)
Mean	562.51	29,193.68	1.18	74.02	29.81
Median	520.00	26,870.75	0.88	75.60	28.22
Std. dev.	329.96	18,374.73	2.61	11.82	18.33
Minimum	0.00	1348.83	0.00	50.62	0.00
Maximum	1821.60	102,913.50	6.31	98.00	99.99
Skewness	0.63	0.70	24.02	−0.15	1.11
Kurtosis	3.45	3.56	626.71	2.23	3.18
Jarque-Bera	55.04 *** (0.0000)	69.79 *** (0.0000)	0.00 *** (0.0000)	21.11 *** (0.0000)	155.00 *** (0.0000)

Note: *** Denotes significance at 1%. Data Sources: (1) [53–55]. (2) [49]. (3) [51]. (4) [50]. (5) [52].

Following the descriptive statistics, Figures 1 and 2 illustrate the development of the percentage of RES participation in the fuel mix relative to the CO_2 intensity of electricity generation from 1995 to 2018. It is evident from the figures that the vast majority of the examined countries during these 24 years incorporated more eco-friendly production units, which had an evident impact on the environmental cost of power production. However, some major pollutants, including in USA, Japan, and Australia, do not seem to have made the necessary progress regarding renewable electricity, while France's low recorded values of carbon emissions are merely due to the extensive use of nuclear power.

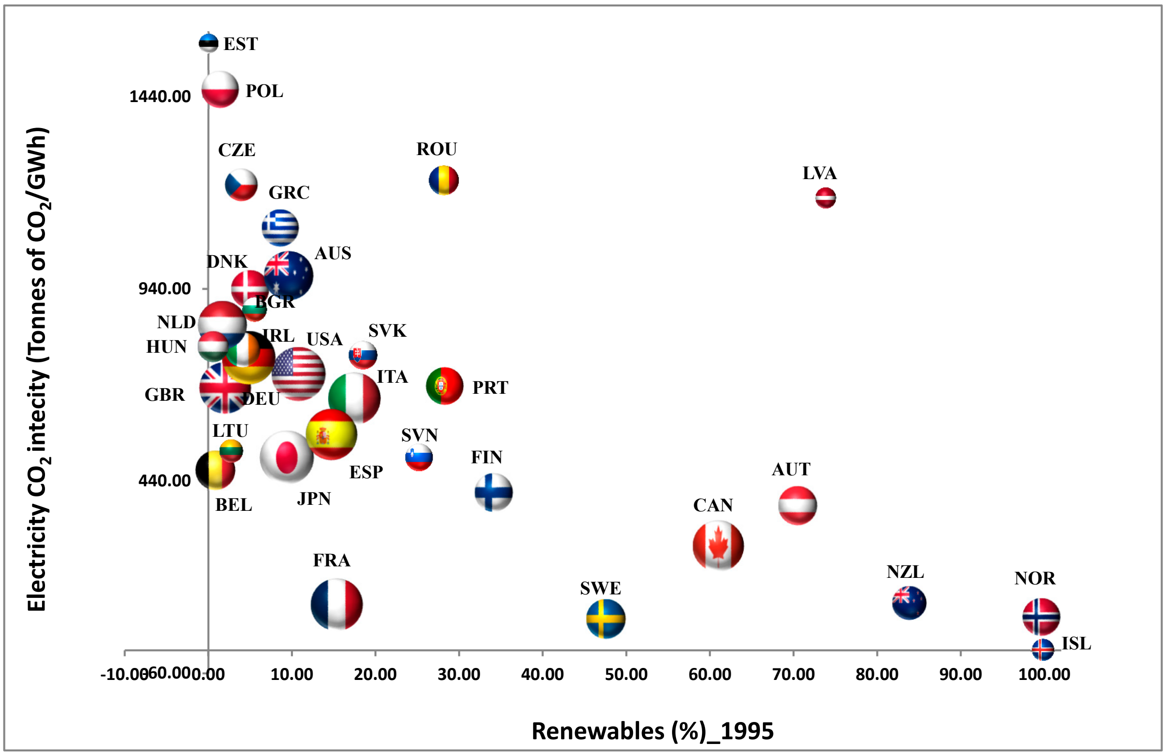

Figure 1. Electricity CO_2 intensity vs. Renewables (%) Year _1995. Note: Sphere size is determined based on each country's Total GDP ranking in the dataset. Authors' elaboration. Data sources: [49,52–55].

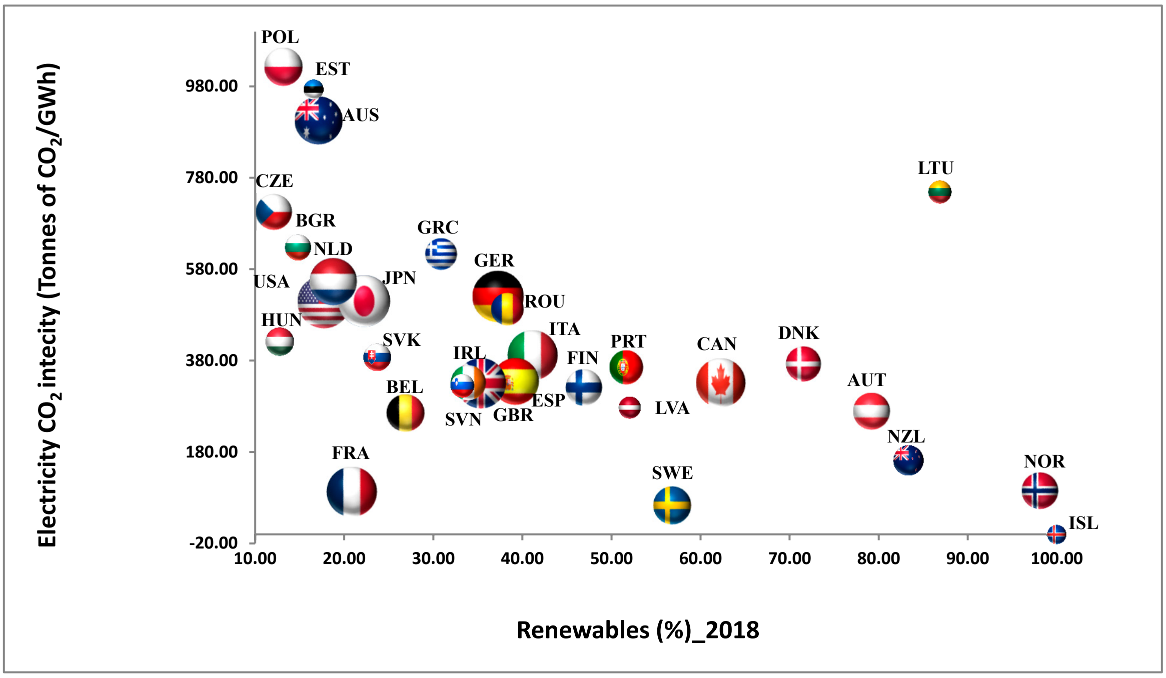

Figure 2. Electricity CO_2 intensity vs. Renewables (%) Year _2018. Note: Sphere size is determined based on each country's Total GDP ranking in the dataset. Authors' elaboration. Data sources: [49,52–55].

Finally, Table 2 portrays the Pearson correlation coefficients between all variables included in the research. What is noteworthy from this table is the low negative but statistically significant correlation between GDP per capita, urbanization, renewables, and electricity CO_2 intensity, as well as the positive and highly statistically significant correlation between renewables and all the other explanatory variables and between urbanization and GDP per capita.

Table 2. Pearson's correlation coefficients.

Variable	Electricity CO_2 Intensity	GDP per Capita	GDP per Capita^2	Electricity GFCF	Urbanization	Renewables	Renewables^2
Electricity CO_2 Intensity	1.0000						
GDP per capita	−0.4772 *** (0.0000)	1.0000					
GDP per capita^2	−0.3927 *** (0.0000)	0.9371 *** (0.0000)	1.0000				
Electricity GFCF	0.0694 * (0.0585)	−0.0495 (0.1778)	−0.0402 (0.2730)	1.0000			
Urbanization	−0.3129 *** (0.0000)	0.5310 *** (0.0000)	0.4155 *** (0.0000)	0.0113 (0.7576)	1.0000		
Renewables	−0.6191 *** (0.0000)	0.3812 *** (0.0000)	0.4002 *** (0.0000)	−0.0026 *** (0.9445)	0.1580 *** (0.0000)	1.0000	
Renewables^2	−0.5684 *** (0.0000)	0.3901 *** (0.0000)	0.4322 *** (0.0000)	0.0160 (0.6629)	0.2196 *** (0.0000)	0.9576 *** (0.0000)	1.0000

Note: *** Note: Denotes significance at 1%, and * at 10% levels, respectively. Numbers in parentheses show the test corresponding *p*-values.

3.2. Causality Testing between Model Variables

To specify the appropriate econometric models, it is considered wise to first examine the potential causality relationships between the sample variables. Hence, a causality analysis was conducted based on the fundamental Granger causality approach and the Dumitrescu and Hurlin (2012) [56] test, with the latter being characterized by looser causality conditions. The test results for 2 lagged periods, which are depicted in Table 3, reveal a statistically significant bidirectional relationship between electricity GFCF, GDP per capita, and electricity CO_2 intensity. Likewise, a two-way effect was detected between GFCF and GDP per capita. Lastly, a unidirectional causal relationship was observed regarding urbanization and renewables with electricity CO_2 intensity and GDP per capita with renewables.

Table 3. Causality testing Lag Order: 2.

Null Hypothesis:	Obs	Test-Statistic	*p*-Value
Electricity CO_2 Intensity does not Granger Cause **GDP per capita**	682	**2.5523**	**0.0107**
GDP per capita does not Granger Cause **Electricity CO_2 Intensity**	682	**7.7634**	**0.0000**
Electricity CO_2 Intensity does not Granger Cause **Electricity GFCF**	682	**2.5363**	**0.0112**
Electricity GFCF does not Granger Cause **Electricity CO_2 Intensity**	682	**3.7923**	**0.0001**
Electricity CO_2 Intensity does not Granger Cause **Urbanization**	682	1.5386	0.1239
Urbanization does not Granger Cause **Electricity CO_2 Intensity**	682	**9.5967**	**0.0000**
Electricity CO_2 Intensity does not Granger Cause **Renewables**	682	1.9598	0.1417
Renewables does not Granger Cause **Electricity CO_2 Intensity**	682	**12.002**	**0.0000**
GDP per capita does not Granger Cause **Electricity GFCF**	682	**5.3219**	**0.0051**
Electricity GFCF does not Granger Cause **GDP per capita**	682	**4.9294**	**0.0075**
GDP per capita does not Granger Cause **Urbanization**	682	0.1142	0.8921
Urbanization does not Granger Cause **GDP per capita**	682	1.4370	0.2384
GDP per capita does not Granger Cause **Renewables**	682	**5.9537**	**0.0027**
Renewables does not Granger Cause **GDP per capita**	682	1.5914	0.2044
Urbanization does not Granger Cause **Electricity GFCF**	682	1.5536	0.2122
Electricity GFCF does not Granger Cause **Urbanization**	682	0.0184	0.9817
Urbanization does not Granger Cause **Renewables**	682	0.8356	0.4340
Renewables does not Granger Cause **Urbanization**	682	0.1253	0.8822
Electricity GFCF does not Granger Cause **Renewables**	682	2.5245	0.0809
Renewables does not Granger Cause **Electricity GFCF**	682	1.8145	0.1637

Note: For the estimation of Granger and [56] Dimitrescu–Hurlin (2012) causality tests, the corresponding statistical functions of the "EVIEWS" software were utilized. Full results for both tests are available upon request.

3.3. Models Specification

Following the conclusions of the causality tests, two model specifications were formed. The basic panel model will investigate the impact of GDP per capita, electricity GFCF, urbanization, and renewables on electricity CO_2 intensity.

Basic Model:

$$CO_{2\ int} = \beta_0 + \beta_1 GDP_{per\ capita\ i,t} + \beta_2 GFCF_{i,t} + \beta_3 Urbanization_{i,t} + \beta_4 Renewables_{i,t} + \varepsilon_{i,t} \quad (1)$$

The given error term ($\varepsilon_{i,t}$) is assumed to be normally distributed with zero mean value and constant variance [42].

In addition, the polynomial model will examine whether the effect of personal income and percentage RES usage on electricity CO_2 intensity changes after a certain point. As a result, the second model contains the extra parameters of GDP per capita^2 and renewables^2.

Polynomial Model:

$$CO_{2\ int} = \beta_0 + \beta_1 GDP_{per\ capita\ i,t} + \beta_2\ GDP^2_{per\ capita\ i,t} + \beta_3 GFCF_{i,t} + \beta_4 Urbanization_{i,t} + \beta_5 Renewables_{i,t} + \beta_6 Renewables^2_{i,t} + \varepsilon_{i,t}{}^1, \quad (2)$$

3.4. Testing for Cross-Section Dependence

Cross-sectional correlation within and among units is often detected in panel data models and can lead to relatively unreliable conclusions and poor strategic planning, as the produced outcome merely relies on biased model parameter estimates. Cross-section dependence between error terms may seriously affect the estimation of both coefficients and standard errors when applying standard panel data econometric techniques.

Table 4 depicts the overall test results for cross-sectional correlation in the models' variables, including the average and absolute correlation coefficients together with the Pesaran (2004) [57] CD test for cross-sectional independence and the Pesaran (2015) [58] CD test for weak cross-sectional dependence. Results for average and absolute correlations reveal the presence of a strong positive pairwise cross-sectional correlation. Furthermore, the outcomes of both the Pesaran (2004) CD test and the Pesaran (2015) CD test show that the null hypothesis in both tests is rejected at the 1% significance level, indicating the presence of strong cross-sectional dependence for all model variables. This is quite reasonable as the GDP per capita, GFCF, and RES deployment are often influenced by common global macroeconomic and environmental developments.

Table 4. Cross-section dependence of panel time series.

Variable	Pesaran (2004) CD_{test}	Correlation	Correlation (Absolute)	Pesaran (2015) Weak CD_{test}
Electricity CO_2 Intensity	46.34 *** (0.0000)	0.439	0.630	101.077 *** (0.0000)
GDP per capita	93.89 *** (0.0000)	0.889	0.889	103.395 *** (0.0000)
GDP per capita^2	90.15*** (0.0000)	0.853	0.853	100.580 *** (0.0000)
Electricity GFCF	7.61 *** (0.0000)	0.072	0.372	90.972 *** (0.0000)
Urbanization	35.72 *** (0.0000)	0.338	0.830	105.585 *** (0.0000)
Renewables	64.40 *** (0.0000)	0.610	0.727	95.756 *** (0.0000)
Renewables^2	65.27 *** (0.0000)	0.618	0.721	89.403 *** (0.0000)

Note: *** Denotes significance at 1%. The null hypothesis (H_0) of the Pesaran (2004) CD test assumes strict cross-sectional independence. The null hypothesis (H_0) of the Pesaran (2015) CD test assumes weak cross-sectional independence. For the Pesaran (2004) CD and the Pesaran (2015) CD tests, the *xtcd* and the *xtcd2* commands of "STATA" software were utilized. Correlation and Absolute (correlation) are the average (absolute) value of the off-diagonal elements of the cross-sectional correlation matrix of residuals.

Similarly, Table 5 presents the statistical outcomes of the tests examining the cross-sectional dependence between individual country panels. For this purpose, the Pesaran (2004) test is employed, together with the non-parametric Friedman (1937) test [59] and Frees (1995) [60] Q-distribution test for cross dependence. In Table 5, it is evident that all three tests strongly reject their null hypothesis for cross-sectional independence at the 1% significance level for both models, thus supporting the existence of cross-sectional dependence in the models' error terms. This finding indicates that shocks are transferred between countries, possibly as a result of applying similar fiscal policies in response to international economic developments. Moreover, the processed dataset consists of developed economies with high GDP per capita, which are affected by similar economic factors, while they need to comply with common environmental rules and achieve mutual goals regarding air pollution (i.e., EU energy policy, Kyoto protocol, Paris agreement, etc.).

Table 5. Cross-Section dependence among groups.

	Basic Model	Polynomial Model
Pesaran's test of cross sectional independence	10.458 *** (0.0000)	13.359 *** (0.0000)
Friedman's test of cross sectional independence	96.876 *** (0.0000)	110.507 *** (0.0000)
Frees' test of cross sectional independence	8.244	5.703
Critical values from Frees' Q distribution:	**Alpha** = 0.10 0.1078	**Alpha** = 0.10 0.1078
	Alpha = 0.05 0.1408	**Alpha** = 0.05 0.1408
	Alpha = 0.01 0.2034	**Alpha** = 0.01 0.2034

Note: *** Denotes significance at 1%. For the Pesaran, Friedman, and Frees group cross-sectional dependence tests, the *xtcsd pesaran abs*, *friedman xtcsd frees xtcsd* post commands after *xtreg* POLS regression in "STATA" software were utilized.

3.5. Panel Unit Root Test

Another crucial step in the panel data econometric analysis is to test for stationarity in the models' variables by applying the necessary unit root test. For this purpose, the current study utilizes the ADF-Fisher panel unit root test. Tables 6 and 7 highlight the stationarity results of the processed data sample, clearly showing that the test statistics at these levels fail to reject the null hypothesis. The models' variables are not stationary at these levels due to the existence of a panel unit root. Nevertheless, when applying tthe first differences to the data, all variables strongly reject the null hypothesis at the 1% significance level, meaning that they are stationary and integrated at order one I(1).

Table 6. ADF–Fisher panel unit root test at level I(0).

Variable	Inverse χ^2 Statistic (p)	Modified Inversed χ^2 Statistic (Pm)	Inverse Normal Statistic (Z)	Inverse Logit Statistic (L)
Electricity CO_2 Intensity	103.0259 ***	3.6842 ***	1.0655	−0.0120
	(0.0008)	(0.0001)	(0.8567)	(0.4952)
GDP per capita	20.6865	-−3.7101	4.3823	4.1194
	(1.0000)	(0.9999)	(1.0000)	(1.0000)
GDP per capita^2	20.7444	−3.7049	4.9410	4.8531
	(1.0000)	(0.9999)	(1.0000)	(1.0000)
Electricity GFCF	79.3312 *	1.5564 *	−1.7302 **	−1.6842 **
	(0.0681)	(0.0598)	(0.0418)	(0.0471)
Urbanization	47.4316	−1.3083	2.1543	2.2479
	(0.9141)	(0.9046)	(0.9844)	(0.9870)
Renewables	22.1894	−3.5751	7.1893	7.7981
	(1.0000)	(0.9998)	(1.0000)	(1.0000)
Renewables^2	23.3734	−3.4688	7.1098	7.8171
	(1.0000)	(1.0000)	(1.0000)	(0.9997)

Note: *** Denotes significance at 1%, ** at 5%, and * at 10% levels, respectively. The null hypothesis (H_0) of the test assumes variable non-stationarity. Numbers in parentheses show the test corresponding p-values. For the ADF–Fisher stationarity test, the *xtunitroot* command of "STATA" software was utilized.

Table 7. ADF–Fisher panel unit root test at first difference I(1).

Variable	Inverse χ^2 Statistic (p)	Modified Inversed χ^2 Statistic (Pm)	Inverse Normal Statistic (Z)	Inverse Logit Statistic (L)
Electricity CO_2 Intensity	478.4146 ***	37.3951 ***	−16.8170 ***	−23.6538 ***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
GDP per capita	290.5592 ***	20.5252 ***	−12.7707 ***	−14.3531 ***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
GDP per capita^2	332.7196 ***	24.3113 ***	−13.9425 ***	−16.4278 ***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Electricity GFCF	341.4535 ***	25.0957 ***	−13.3819 ***	−16.7344 ***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Urbanization	84.7092 ***	2.0393 ***	−1.7676 ***	−1.9244 ***
	(0.0293)	(0.0207)	(0.0386)	(0.0280)
Renewables	405.2631 ***	30.8259 ***	−14.3857 ***	−19.6564 ***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Renewables^2	381.7343 ***	28.7130 ***	−13.0039 ***	−17.9590 ***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)

Note: *** Denotes significance at 1%. The null hypothesis (H_0) of the test assumes variable stationarity at least in one panel. Numbers in parentheses show the test corresponding p-values. For the ADF–Fisher stationarity test, the *xtunitroot* command of "STATA" software was utilized.

3.6. Panel Cointegration Tests

After testing for the panel unit root, it is essential to examine the models' variables for co-integration. For this purpose, the Westerlund (2007) [61] co-integration test was first utilized. The specific test, having the advantage of allowing for cross-sectional dependence, is more suitable than other similar tests in this case. The test statistics in Table 8 emphatically reject the null hypothesis of no co-integration between the dataset variables at the 1% significance level, except for the case of urbanization, which shows mixed results. It is reasonable then to assume that electricity CO_2 intensity is co-integrated with GDP per capita, electricity GFCF, RES, and most likely urbanization.

Table 8. Westerlund panel cointegration test.

Equation	Statistic			
	G_τ	G_α	P_τ	P_α
CO_2 Elec Int = f (GDP per capita)	−3.076 *** (0.000)	−13.551 (0.104)	−28.254 *** (0.000)	−15.741 *** (0.000)
CO_2 Elec Int = f (GDP per capita)^2	−2.880 *** (0.000)	−13.487 (0.114)	−25.523 *** (0.000)	−15.681 *** (0.000)
CO_2 Elec Int = f (GFCF Electricity)	−2.695 *** (0.012)	−11.846 (0.554)	−19.268 *** (0.000)	−12.772 *** (0.000)
CO_2 Elec Int = f (Urbanization)	−2.712 *** (0.009)	−7.438 (1.000)	−12.821 (0.113)	−7.262 (0.935)
CO_2 Elec Int = f (Renewables)	−3.025 *** (0.000)	−12.237 (0.427)	−23.110 *** (0.000)	−13.720 *** (0.000)
CO_2 Elec Int = f (Renewables)^2	−3.027 *** (0.000)	−12.189 (0.442)	−22.424 (0.000)	−14.273 (0.000)

Note: *** Denotes significance at 1%. Test regression fitted on a constant and trend with one lag. Kernel bandwidth was set following Demetriades and James (2011) [62]. The null hypothesis (H_0) of the Westerlund panel cointegration test assumes no co-integration in some or all of the panels. The Westerlund test was estimated by using the *xtwest* command with lags(1), leads(1), and lrwindow(3) options of "STATA" software. Numbers in parentheses denote *p*-values.

Since the investigated panel variables were found to be first-order stationary, the Pedroni (1999, 2004) co-integration test [63] was also applied. Five out of seven test statistics in Table 9 reject the null hypothesis for joint non-co-integration at the 5% level. The outcomes obtained by both tests categorically confirm interactions between the dataset's variables.

Table 9. Pedroni Panel Cointegration Test.

	Panel v-Statistic	Panel rho-Statistic	Panel t-Statistic	Panel ADF-Statistic	Group rho-Statistic	Group t-Statistic	Group ADF-Statistic
Test-Statistics	−2.059	3.958	−2.608	0.8478	6.131	−3.133	1.132

Note: All Test-Statistics are distributed N(0,1) and diverge to negative infinity except for panel v, in which the Test-Statistic diverges to positive infinity. The null hypothesis (H_0) assumes no cointegretion of the models' variables. The probability upon which it is decided whether to reject or accept the H_0 it is estimated based on the z-score of the values of the Test-Statistics.

3.7. Heteroskedasticity, Serial-Correlation and Omitted Variable Tests

The final and critical stage prior to proceeding to the main econometric analysis of the two models involves a series of diagnostic tests. First, the two models are examined for the presence of heteroskedasticity by utilizing four representative tests according to the academic literature. This group of tests includes Breusch–Pagan (1979) [64], Glejser (1969) [65], Harvey (1976) [66], and White (1980) [67] heteroskedasticity tests, all of which verify the presence of heteroskedasticity as shown in Table 10. This finding signifies that the variance of the error term in both models is not constant, which is most common when processing data samples with economic and environmental variables. Furthermore, the Breusch–Godfrey/Wooldridge (2010) [68] test is utilized to investigate the existence of serial correlation in the two models, with the null hypothesis for no-serial correlation being rejected at the 1% significance level. Finally, the results of the omitted variables RESET test indicate that the equation of the polynomial model is well-specified while the opposite stands for the basic model. Nevertheless, such mixed results were expected since the POLS methodology is not the appropriate technique to examine such types of variables.

3.8. Econometric Modelling

Since the presence of cross-sectional dependence, heteroskedasticity, and serial correlation was verified for both models, it is essential to make use of the most appropriate econometric methodologies that will guarantee the robustness of the final results upon which the potential policy suggestions will rely on. The econometric analysis is separated into two parts, with the first part including the static analysis and the second part focusing on the potential dynamic effect of the models' parameters.

Table 10. Model diagnostic tests.

	Basic-Model		Polynomial-Model	
	Statistic	*p*-Value	Statistic	*p*-Value
Breusch-Pagan Heteroskedasticity test	31.82 ***	0.0000	21.71 ***	0.0000
Glejser Heteroskedasticity test	30.02 ***	0.0000	31.73 ***	0.0000
Harvey Heteroskedasticity test	20.33 ***	0.0000	23.77 ***	0.0000
White Heteroskedasticity test	29.83 ***	0.0000	47.01 ***	0.0000
Breusch-Godfrey/Wooldridge Serial Correlation test	467.98 ***	0.0000	449.43 ***	0.0000
RESET omitted variable test	11.39 ***	0.0000	0.97	0.4064

Note: *** Denotes significance at 1%. The null hypothesis (H_0) of the Breusch–Pagan (1979), Glejser (1969), Harvey (1976), and White (1980) tests assumes no heteroskedasticity in the models. Similarly, the null hypothesis (H_0) of the Breusch–Godfrey/Wooldridge (2010) test assumes no-serial correlation, (pbgtest {plm} from "R" software). Finally, the null hypothesis (H_0) of the RESET test assumes no omitted variables (*ovtest* post command after *regress* POLS regression in "STATA" software).

3.8.1. Static Modelling

The static econometric analysis requires a number of control tests that will guide the researcher through the selection of the proper methodology. First, a poolability test was applied to specify the stability of POLS model and its effectiveness when compared to a Fixed Effects model. Results for both models strongly point in favor of the appropriateness of the Fixed Effects model. Likewise, the POLS model is further rejected when tested vs. the Random Effects model, based on the Breusch–Pagan (1980) test [69], with the test results indicating significant variance across country panels, hence the existence of a panel effect. Since POLS was proven to be inferior to the Fixed Effects model, it is considered wise to investigate whether the latter is in fact well defined as a model. For this purpose, the study relies on the outcome of the joint significance F-test (ui = 0) of the two models, which clearly shows that the Fixed Effects model is adequate for the current analysis, having the necessary explanatory power. Furthermore, in order to fully specify the Fixed Effects model, it is crucial to determine whether the Time Fixed Effects variation of the model is required to be implemented into the analysis. In this case, the null hypothesis of no time effects in the data cannot be rejected in either of the examined models; hence, the standard individual-effects methodology is more suitable for the analysis.

According to Wooldridge (2010) [68], the Fixed Effects model provides the advantage of dealing with any potential omitted variable bias, while at the same time, it eliminates systematic cross-country differences. These two facts mean, by definition, the Fixed Effects methodology is more suitable to model and process the examined dataset. What is more, the outcome of the Hausman (1978) test [70] reported in Table 11 dictates the dummy control of the time invariant heterogeneity as suggested by the Fixed Effects methodology, hence constituting the Fixed Effects model more appropriate compared to the Random Effects model. Taking all of the above information into consideration, and in order to enhance the predictability and the robustness of the Fixed Effects model in the presence of verified cross-sectional dependence, heteroskedasticity, and serial correlation, the Driscoll–Kraay (1998) [71] standard error estimator is employed.

3.8.2. Dynamic Modelling

Despite the plethora of advantages of the Fixed Effects model with the Driscoll–Kraay (1998) standard error estimator, the model can indeed lead to biased estimates whenever the investigated underlying process is dynamic. One way to control this contingency is to incorporate the dynamic GMM methodology. Moreover, dynamic panel models are more capable than static models in accounting for heterogeneity. The System-GMM model, proposed by Blundell and Bond (1998) [72], constitutes the most robust estimator in dynamic panel modelling, making it superior to other similar methodologies such as the Difference-GMM model. The System-GMM approach is more reliable in terms of avoiding large finite sample bias and low accuracy in cases of persistent time-series. Furthermore, the System-GMM model bears the extra advantage of considering the potential endogeneity of explanatory variables that are not included in the model. It is quite usual for an investigated relationship to contain unobserved effects concerning both the dependent and independent variables at the same time. Likewise, the use of lagged dependent variables as instruments in the System-GMM model may prove to be vital since valid external instruments are relatively difficult to create.

Table 11. Diagnostic tests for static econometric analysis.

	Basic-Model		Polynomial-Model	
	Statistic	***p*-Value**	**Statistic**	***p*-Value**
Poolability test	21.370 ***	0.0000	17.171 ***	21.532
Breusch-Pagan LM test	4900.3 ***	0.0000	4760.6 ***	0.0000
Joint significance F-test (FE)	90.95 ***	0.0000	93.06 ***	0.0000
Time-Effects test (FE)	0.275	0.9997	0.299	0.9995
Hausman test	8.81 **	0.0319	16.47 ***	0.0056

Note: *** Denotes significance at 1%, ** at 5% respectively. For the Poolability test, the *Pooltest* of *plm* package of "R" software was applied. The null hypothesis (H_0) of the *Pooltest* assumes stability of the POLS model and robustness when compared to a Fixed Effects model. To examine the existence of a panel effect in the data, the Breusch–Pagan LM test (1980) of *plm* package of "R" software was utilized. The null hypothesis (H_0) of the Breusch–Pagan LM test (1980) assumes no panel effect, implying that the POLS model is more effective than a Random Effects model. The joint significance F-test (u_i = 0) in Table 11 is the one reported in the statistics table of a Fixed Effects model using the *xtreg* command of "STATA" software. To investigate whether it is necessary to implement the Time-Fixed-Effects model relative to the basic Fixed-Effects model with individual effects, the *pFtest* of *plm* package of "R" software was used. The null hypothesis (H_0) of the *pFtest* assumes the presence of significant time effects, implying the superiority of the Time-Fixed-Effects model relative to the basic Fixed-Effects model. Finally, the Hausman (1978) test of "STATA" software with the *sigmamore* option was applied to select between the dummy control of time-invariant heterogeneity and its potential random disperse in the error term, as implied by the Fixed Effects and the Random Effects methodology, respectively.

Nonetheless, all the previously mentioned advantages come at the cost of strict orthogonality conditions. First of all, the AR(1) and AR(2) serial correlation tests of Arellano and Bond (1991) [73] for the differenced error terms need to be reported, requiring the AR(2) test to exhibit no second-order serial correlation in order for the model to be well specified and able to provide robust results. Additionally, for large panel datasets including multiple periods, instruments are likely to exceed the number of endogenous variables. For this purpose, the Hansen-J overidentification test is utilized to determine the validity of the instruments, as well as the instrument quality based on the level and difference equations.

The present econometric analysis merely relies on the System-GMM methodology, with Windmeijer's (2005) [74] corrected standard errors and orthogonal deviations to test the potential dynamic relationship between the dependent and independent variables of the proposed models. It has been repeatedly empirically proven in academia that the two-step System-GMM model provides more robust estimates in comparison with the one-step model; likewise, the same applies to the one-step and two-step Difference-GMM models. Consequently, the dynamic analysis there will put more weight on the two-step System-GMM model, with the relative results for the two-step Difference-GMM model also being reported. Finally, it is essential to mention that in the study's GMM analysis, the model instruments are structured with the use of both level and first-difference equations. This procedure increases the number of instruments, allowing the produced outcomes of the two-step GMM model to meet the fundamental methodological conditions while remaining insightful in the event of potentially endogenous regressors.

4. Empirical Analysis and Results

Table 12 contains the empirical results of both static and dynamic econometric analysis. In the static analysis, the outcomes for the basic Fixed Effects model with Driscoll–Kraay (1998) [71] standard errors show that GDP per capita, electricity GFCF, and renewables are statistically significant at the 1% level, in contrast to urbanization, which does not seem to affect electricity CO_2 intensity. Specifically, a 1% increase in GDP per capita and renewables causes, ceteris paribus, a decrease in electricity CO_2 intensity of 0.0031%, and 2.6553%, respectively, while a 1% increase in electricity GFCF creates a high upward trend in carbon emissions of approximately 2.6097%. The estimates for the polynomial model further confirm the previous findings, implying that electricity CO_2 intensity is elastic with respect to GDP per capita, electricity GFCF, and renewables. Interestingly, the econometric results for the polynomial model reveal the existence of a U-shaped relationship between GDP per capita and electricity CO_2 intensity, as well as between renewables and electricity CO_2 intensity, with the two explanatory variables first being negative in the linear mode and then slightly positive in the squared mode. These rather intriguing outcomes suggest that the increase in GDP per capita and RES deployment initially decrease electricity CO_2 intensity, yet beyond a certain level of income and renewable energy usage, any further rise causes exactly the opposite effect. The turning point for GDP per capita is estimated at approximately $58,670 USD, while for renewables, it is 52.62% of the total fuel mix.

Table 12. Empirical findings under different specifications.

Variable	Static-Analysis		Dynamic-Analysis	
	Basic-Model Polynomial-Model		Basic-Model	
	Fixed Effects Driskoll-Kraay (S.E) Fixed Effects	Fixed Effects Driskoll-Kraay (S.E)	Difference-GMM (2-Steps)	System-GMM (2-Steps)
CO_2 Electricity Intensity$_{(t-1)}$	-	-	0.6873 ***	0.6880 ***
	-	-	(0.0000)	(0.0000)
GDP per capita	−0.0031 ***	−0.0113 ***	−0.0016 ***	−0.0015 ***
	(0.000)	(0.000)	(0.0000)	(0.0000)
GDP per capita^2	-	9.63×10^{-8} ***	-	-
	-	(0.000)	-	-
GFCF Electricity	2.6097 ***	2.8675 ***	9.2446 ***	10.8065 ***
	(0.005)	(0.0000)	(0.0000)	(0.000)
Urbanization	−3.6626	−2.1194	−4.4343 **	−4.4770 ***
	(0.1190)	(0.3090)	(0.0157)	(0.0035)
Renewables	−2.6553 ***	−5.3984 **	−1.4997 ***	−1.3879 ***
	(0.000)	(0.0180)	(0.0000)	(0.0000)
Renewables^2	-	0.0513 *	-	-
	-	(0.0830)	-	-
Constant	1000.02 ***	1007.034 ***	-	-
	(0.000)	(0.000)	-	-
AR(1) (*p*-value)	-	-	0.0370	0.0330
AR(2) (*p*-value)	-	-	0.3260	0.3220
Hansen-J test (*p*-value)	-	-	0.3809	0.5061

Note: *** Denotes significance at 1%, ** at 5%, and * at 10% levels, respectively, with the numbers in brackets indicating the corresponding *p*-values. For the static analysis, the Fixed Effects commands *xtreg* and *xtscc* of of "STATA" software were applied. For the dynamic analysis and the Difference-GMM and System-GMM models, the corresponding statistical functions of the "EVIEWS" software were utilized. AR(1) and AR(2) are tests for first- and second-order serial autocorrelation. The Hansen-J denotes the test of over-identifying restrictions of the instruments in the System-GMM model.

In Dynamic panel analysis, the two-step Difference and System-GMM models were implemented with one period lag for the dependent variable. In this way, the potentially dynamic effect of the model covariates on electricity CO_2 intensity is captured. The high statistically significant coefficients for the lagged electricity CO_2 intensity prove that the current value of the variable is correlated with its former ones. Irrespective of which of the Difference-GMM and System-GMM methodologies are used to process the basic model, all four explanatory variables remain statistically significant at the 1% level. This outcome of dynamic analysis for urbanization suggests that the level of importance and the magnitude of the actual effect of this parameter needs at least one period until it is fully reflected in the power sector's CO_2 emissions. A rise in the urban population of 1% appears to be sufficient to deliver a remarkable reduction in electricity CO_2 intensity in the region of −4.4770%. In harmony with the static analysis results, carbon emissions of electricity generation are found to be elastic with respect to GDP per capita, electricity GFCF, and renewables. Concretely, a 1% increase in GDP per capita and renewables ceteris paribus triggers a decrease in electricity CO_2 intensity of −0.0015% and −1.3879%, respectively, whereas a 1% increase in electricity GFCF causes exponential growth in CO_2 emissions of approximately 10.8065%.

It is worth noting that the coefficients for GDP per capita and renewables are proven to be much lower than those initially estimated in the static analysis, though with analogous statistical significance, signifying that their impact on electricity CO_2 intensity is partly absorbed by its lagged values. This difference can be attributed to the dynamic relationship between electricity CO_2 intensity and the two variables, revealing that the static Fixed Effects model overstated their actual influence. In contrast, the coefficients for urbanization and electricity GFCF are considerably higher than in the static analysis, implying that the real impact of these two parameters needs at least one period to become fully apparent in the power sector's carbon emissions.

The fact that the lagged dependent variable was found positive and statistically significant at the 1% level helps the researcher draw some additional and very useful conclusions relative to electricity CO_2 intensity. This outcome essentially shows that the current value of electricity CO_2 intensity is highly correlated with its previous ones. Furthermore, when the lagged dependent variable is found statistically significant, the coefficient allows for the estimation of the variable's convergence rate with respect to adjustments in the examined model's explanatory variables. In this case, the adjustment in the amount of electricity generation carbon emissions proceeds at a rate of 31.2% per annum (1–0.6880), suggesting that only one-third of the discrepancy between the anticipated and real levels of the electricity sector's CO_2 can be eliminated within one period. Based on this discovery, it requires approximately 3 years for the full convergence of electricity CO_2 intensity relative to changes in the four explanatory variables.

Figures 3 and 4 present the electricity CO_2 intensity in relation to GDP per capita and of renewable usage.

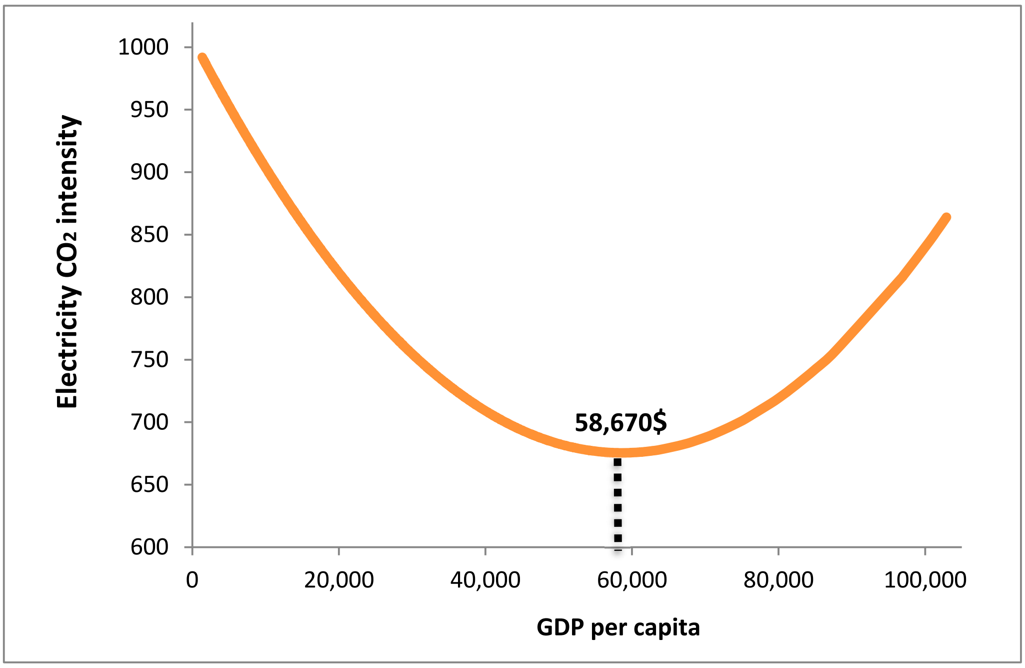

Figure 3. Electricity CO_2 intensity vs. polynomial function of GDP per capita.

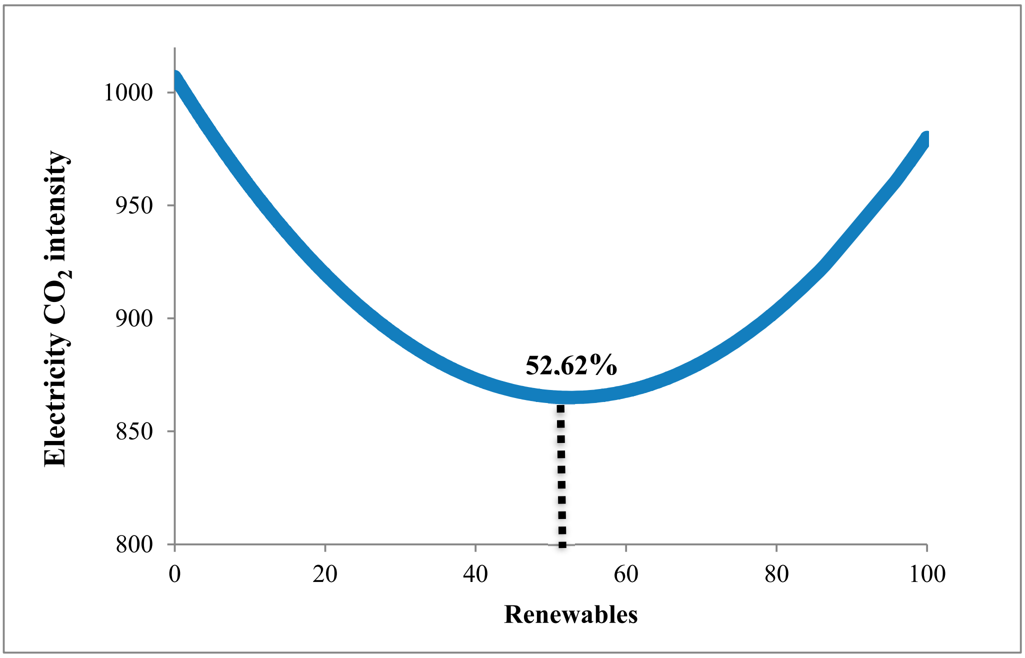

Figure 4. Electricity CO_2 intensity vs. polynomial function of Renewables usage.

5. Discussion and Policy Implications

5.1. GDP per Capita

Based on the econometric outcomes presented in Section 4, it is evident that the relationship between electricity CO_2 intensity and GDP per capita is of a quadratic form, creating a U-shaped curve. As a result, the effect of the rising GDP per capita is found to decrease the power sector's emitted CO_2 up to the turning point of 58,670 USD. Although seemingly unexpected, it must be taken into consideration that the present study solely examines the impact of GDP per capita on electricity generation and specifically on the ratio of CO_2 emissions per generated GWh.

A reasonable explanation for this U-shaped connection is that the processed dataset is comprised of highly developed countries, in which consumers are more willing to pay for eco-friendly electricity. Wealthy societies with great quality-of-life standards provide their citizens broad access to high-level education, allowing them to grow strong environmental awareness, which makes "green" energy more attractive. Gradually increasing the GDP per capita seems to become a positive driver for the reduction of electricity carbon emissions, yet for income levels higher than 58,670 USD, this effect appears to be reversed. This finding can be justified by the fact that beyond a certain income level, a substantial part of the population is wealthy enough to purchase more sophisticated high-tech devices and other luxury products. As a general rule, the production process of these types of goods requires vast amounts of energy, while their operational electricity consumption tends to be considerably high.

Since electricity demand is the main contributor to carbon emissions, it would be wise for central governments and major organizations such as the EU to set stricter environmental rules regarding high-tech product manufacturing. Additionally, it is crucial to set specific energy efficiency standards that will not allow electricity-intensive products to reach the market. A characteristic example is electric cars, as both their mass production and their everyday use require substantial amounts of electricity. Consequently, an energy strategy based on unconditionally subsidizing the purchase of electric cars can prove to be rather inefficient in terms of CO_2 reduction. Most times, electric cars do not replace the buyers' conventional technology cars (e.g., they are used by households as second cars) and they are not adequately energy efficient, thus becoming an extra burden for the power system and adversely affecting carbon emissions. Simply taking measures that exclusively set the increase in the electric cars market share as the objective does not guarantee sustainable development. Such a strategy may negatively impact electricity demand and indirectly increase electricity CO_2 intensity since simply going electric does not necessarily mean going "green". Subsidy policies similar to those recently incorporated by the EU need to be carefully reconsidered, as the invested funds may fail to serve their primary goal and eventually result in a minor or even harmful effect on energy resource self-sufficiency and environmental protection.

What is more, the Granger and Dimitrescu–Hurlin (2012) causality tests confirmed a bidirectional relationship between electricity CO_2 intensity and GDP per capita. This reasonable finding essentially reveals that power production from fossil fuels contributes to economic growth. At present, power systems in most countries require the purchase of immense amounts of energy products from several importers, refiners, and distributors. This extremely profitable market is currently an integral part of electricity generation, as well as the main activity sector for numerous enterprises. Considering the economic importance of this market and its extensive inter-reliance with the electricity sector, one can comprehend the reasons behind the delay and the occasional unwillingness of state authorities to develop a sustainable power system primarily relying on renewable electricity. Such a complex task would entail the radical overhaul of the power sector and the transition to a new era in which RES would play the leading role.

Nonetheless, in the case of an abrupt transformation of the electricity market, both firms and households would be deprived of valuable time, which would allow them to successfully acclimatize to such fundamental progress. The predominance of RES as the principal means of electricity production may be subject to subsequent economic costs and job losses due to skill incompatibility, hence diligent planning is required for the simultaneous and rapid development of the RES industry in order to offset the adverse repercussions of such development.

5.2. Urbanization

The degree of the urbanization process often approximates a country's stage of development, with the progressing stage of urbanization also being closely related to energy consumption. The econometric analysis in the present study has made clear that the vast majority of the countries in the dataset have not yet reached the critical stage of the over-concentration of a population; hence, a further increase in urbanization would still have a considerable positive impact on electricity demand and electricity CO_2 intensity.

Urbanization levels are likely to continue rising in the near future, urging governments of the countries included in the study to implement energy efficiency policies with respect to existing public urban infrastructure and promote energy-saving projects for households and enterprises. Modern, multipurpose, and eco-friendly public buildings and transportation, combined with attractive financial incentives for the energetic refurbishment of houses, offices, and production units, would enhance, if not multiply, the beneficial effect of urbanization on electricity demand. Lowering the electricity demand and especially the peak demand will allow for covering a substantial amount of electricity generation from RES, decisively contributing to the self-sufficiency and sustainability of the power sector.

Despite the high energy-saving prospects that urbanization offers, if not closely monitored by central governments, it may also act as a compounding factor of electricity demand, jeopardizing any effort for a sustainable electricity future. An excessive level of urbanization is found to be closely linked to the creation of massive and dysfunctional megalopolises with gradually growing energy needs. According to [13], the additional required amount of electricity in these gigantic cities is, in most cases, covered by increasing the production of existent fossil fuel power plants, thus worsening the overall carbon footprint of electricity generation. Finally, countries with large and growing metropolitan cities are highly likely to deal with extensive air pollution levels, as they may no longer benefit from the economies of scale that public services and infrastructure tend to create.

5.3. Renewables

The empirical analysis revealed a quadratic U-shaped relationship between RES and electricity CO_2 intensity. RES participation in the electricity fuel mix has an initially positive and significant impact, which results in the reduction of carbon emissions. Yet, for a total RES dependence exceeding 52.65%, this effect appears to gradually reverse. Although seemingly a paradox, this finding is reasonable since the current technological level of RES and electricity storage does not allow dealing with the peak demand. Consequently, relying on renewable electricity production beyond a certain point requires the engagement of auxiliary carbon-intensive units to handle any unexpected spikes in electricity demand and secure the grid's supply quality. RES expansion is the best answer to the massive and mounting environmental and economic costs of fossil fuel usage; however, energy transitions are predominantly non-linear and trigger multiple unexpected implications.

At present, considering RES deployment as a perfect substitute for conventional fossil fuel power plants sounds rather utopian, mostly due to RES's inability to cover periodically excessive electricity demand. Renewable electricity generation still needs to be accompanied by quick dispatch oil, gas, and coal-fired power plants that may be required to operate even at full capacity whenever a gap appears between the flat production rate of RES and the actual electricity demand. Hence, immoderately raising the participation of RES in the generation scheme can prove to be a fairly inefficient strategy, since crossing the estimated turning point is expected to adversely affect the CO_2 intensity of electricity.

RES can undoubtedly play a key role in the power sector's self-sufficiency and sustainability. The fact that renewables are able to generate significant amounts of "green" electricity without requiring any input fuels makes them a major contributing factor in the battle for energy autonomy and sustainable economic development. RES deployment diminishes energy import needs, enabling governments to minimize any relative geopolitical dependencies.

The analysis of the processed dataset showed that the mean and median values of RES dependence are approximately 28%, which is significantly below the estimated turning point. This means that the vast majority of the countries included in the study can decisively improve their level of electricity generation self-sufficiency and sustainability by intensifying efforts for RES expansion. Increasing investments in RES will enable these countries to considerably boost economic growth in an eco-friendly way, while at the same time managing to moderate CO_2 emanations.

The limitations of the current technological level of RES attest that there are many vital innovations and much progress to be achieved until they are truly capable of replacing fossil fuel power plants in a reliable way. A critical issue that always remains is the improvement of RES efficiency. Nevertheless, perhaps the most important field for R&D concerns the necessary technological advances regarding electricity storage infrastructure, which will enable system controllers, when necessary, to supply the grid with extra electricity.

5.4. Electricity Sector's GFCF

Both static and dynamic econometric analyses unveiled a strong positive bidirectional relationship between electricity CO_2 intensity and power sector GFCF. The substantial effect of GFCF on carbon emissions mainly reflects the fact that a large amount of capital is being invested in carbon-intensive technologies (i.e., Coal, CHP, and natural gas electricity factories), thus increasing the carbon footprint of electricity generation. This finding suggests that traditional power plants are still a far more profitable investment than RES production units.

The great impact size of GFCF on electricity carbon emissions shows that the current level of new investments is high enough to contribute in a decisive way to the process of developing a "green" and sustainable power system. However, the amount of investment concerning cleaner production processes remains relatively low despite a plethora of joint efforts (energy and environmental taxes, GHG permits, the emission trading system (ETS), etc.) from national and international authorities. In addition to certain limitations on CO_2 emissions, the change in the current status quo in the power sector also requires a stricter legal framework with respect to the minimum permissible percentage of new investments concerning carbon-free technologies. Effectively incorporating such an energy strategy poses a major challenge for every government worldwide, as it would result in directing substantial cash flows into RES deployment and R&D.

Furthermore, the bidirectional relationship between GDP per capita and the electricity sector's GFCF depicts the necessity for continuous economic growth, so that more capital is available to upgrade the existing electricity infrastructure and facilitate the clean energy transition. Electricity generation sustainability not only enhances environmental upgrades but also ensures the quality of power supply, which is a vital condition for firm profitability. A self-sufficient power system combined with an advanced transmission network literally constitutes the cornerstone of a competitive and prosperous industrial sector and a continuously growing GDP.

6. Conclusions

Although theoretically a positive driver of electricity demand and carbon emissions, it was revealed that for high levels, GDP per capita can become an aggravating factor of electricity CO_2 intensity. High available income influences the purchase of high-tech goods, of which both production and daily use require vast amounts of electricity. Consequently, energy strategies involving subsidy programs on products such as electric cars should be wisely reconsidered.

The present study also verified the immense importance of electricity GFCF and urbanization in an effort to control global warming and stimulate low-cost electricity production. The radical restructuring of the electricity market and a shift to an era where "green" energy will be dominant necessitates restrictive measures that will decisively moderate carbon emissions. The analysis showed that, until the present, conventional carbon-intensive production units seem to remain a far more preferable investment than RES. For this reason, it is critical for central governments to establish a strict legal framework, which will oblige a certain minimum percentage of new power generation investments to concern RES deployment. What is more, it was discovered that the countries included in the dataset have not yet reached the stage of urbanization by which electricity CO_2 intensity is negatively affected. Therefore, by closely monitoring the urbanization process and financially motivating energy-saving projects, state authorities can take advantage of the beneficial effect of urbanization and further boost the process of RES expansion and CO_2 abatement.

Upon investigating the relationship between RES and electricity CO_2 intensity, it was revealed that extending RES's participation in the generation scheme over the optimal level of 52.65% results in an adverse effect on the electricity carbon footprint. Due to the limitations that stem from the current technological level of RES's efficiency and electricity storage capacity, immoderately increasing RES deployment can jeopardize the vital goal of effective GHG abatement. This outcome urges governments and international organizations such as the EU to provide extensive funding to universities and research centers for R&D purposes in order to promote and accelerate the necessary technological progress.

Finally, it is important to mention that, despite its rather interesting and intriguing outcomes, the paper is subject to certain limitations that may become the basis for future research. Specifically, the processed dataset utilized for the econometric analysis does not cover a crucial time period from 2018 until 2022 during which the global pandemic of COVID-19 and the military conflict in Ukraine took place, while the study only provides short-term and non-dynamic estimates of the turning points for the GDP and RES effect, respectively.

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Abbreviations

EU	European Union
GPD	Gross Domestic Products
GFCG	Gross Fixed Capital Formation
GWh	Giga Watt hour
RES	Renewable Energy Sources
UN	United Nations

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