



Impact of Clean Energy Integration on CO₂ Intensity in European Power Systems

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Abstract: This paper examines the impact of clean energy integration on CO₂ intensity in European power systems over 2015–2024, based on a dataset of 38 European countries. The study applies three analyses: (i) descriptive statistics on cross-country patterns (ii) fixed-effects regression on clean energy and CO₂ intensity, and (iii) crisis-period modelling for 2021–2022. The descriptive results reveal significant heterogeneity. The average clean energy share is 30.8%, ranging from below 5% (Malta, Moldova) to above 45% (France) and approximately 38% (Sweden). Accordingly, CO₂ intensity varies between 23.6 gCO₂/kWh (Sweden) and 982 gCO₂/kWh (Kosovo), indicating different decarbonization rates across Europe. Regression analysis provides statistically significant evidence that clean energy is associated with lower carbon intensity. A one-point increase in the share of wind and solar power corresponds to a reduction of 12.18 gCO₂/kWh ($p < 0.01$), while a similar increase in other clean sources (hydroelectric, nuclear) corresponds to a decrease of 12.24 gCO₂/kWh ($p < 0.01$). Electricity demand has no statistically significant relationship with CO₂ intensity. Crisis-era modeling shows insignificant interaction terms for 2021–2022, suggesting stability of the relationships during the crisis. Overall, the findings support the importance of clean energy integration, highlight persistent inequalities across countries, and the value of policy resilience during major energy shocks.

Keywords: Clean energy integration, CO₂ intensity, European power systems, Decarbonisation, Energy transition.

1 Introduction

Decarbonizing the energy sector is considered one of the most critical areas in the struggle against global climate change. Dependence on fossil fuels for electricity generation accounts for a considerable fraction of total greenhouse gas emissions and poses risks for energy supply security [1, 2]. The European Union (EU) has adopted notably ambitious regional decarbonization targets following the Paris Agreement and has set its vision of net-zero emissions by 2050 [3]. In this context, policies aimed at increasing the share of renewable energy sources, managing electricity demand more

efficiently, and reducing emission intensity constitute the core of the European energy transition [4, 5].

The transformation of the European electricity sector has been examined from multiple perspectives in the literature. Some studies have specifically analyzed the impact of increasing the share of renewable energy on carbon intensity and confirmed their efficacy in reducing the carbon intensity of clean energy investments [6, 7]. Other studies show that the increase in electricity demand leads to an increase in intensity from marginal generation sources [8]. Moreover, the natural gas supply constraints and price shocks of the 2021–2022 energy crisis triggered a resurgence of coal use in many countries. This shift resulted in sudden, sharp increases in carbon intensity indicators [9, 10].

Wind and solar play a special role in the transformation of European energy policies. The variable nature of these resources brings seasonal and annual fluctuations in carbon intensity [11]. Previous research has shown that increasing the share of variable renewable energy reduces intensity in the long term; however, the short-term effects may be limited in cases of demand shocks and low hydro production [12, 13]. Furthermore, resilience in the decarbonization process depends significantly on the diversification of the clean energy portfolio and the balance of the fuel mix in the electricity system [14].

Existing literature documents the long-term transformation of the European electricity sector. For example, Geels [15] points out that energy transitions have technological and socio-political dimensions. Newbery [16] examines the regulatory framework for low-carbon investments in European electricity markets. Furthermore, reports published by international organizations (IEA, IRENA, Ember) highlight the strong correlation between renewable energy penetration and carbon intensity [17–19]. However, panel data regression analyses are still limited, and studies based on large datasets covering 2015–2024 are particularly scarce.

The main contribution of this study is to systematically analyze the effects of clean, fossil, wind, solar, and electricity demand (TWh) on CO₂ intensity using annual indicators derived from Ember’s monthly dataset. This quantitatively demonstrates the decarbonization trends in the European electricity sector and assesses the deviations in intensity dynamics, particularly during the energy crisis. The data used in the study covers 38 geographies and the period 2015–2024. This comprehensive analysis considers the long-term trends in the decarbonization process in Europe, the disruptions caused by the energy crisis, and the effectiveness of clean energy investments.

This study’s findings significantly contribute to academic literature and European energy policy discussions. In particular, the observed decrease in CO₂ intensity, driven by the increasing share of clean energy even during crisis periods, has important implications for energy security and resilience. The results further highlight the importance of accounting for cross-country differences in policy design and, in this respect, provide valuable insights for discussions on the EU’s 2030 emission reduction targets and its long-term net-zero vision.

2 Data and Methodology

2.1 Data Source and Scope

This study uses the European subset of Ember’s monthly electricity database [20]. It includes monthly data on electricity generation, fuel mix, demand, trade flows, and power sector emissions. The analysis covers 10 years of observations from 2015 to 2024. The European sample consists of 38 European countries, according to Ember’s definition of “country or economy”. This dataset was selected because it provides up-to-date, comparable, and systematic information on the decarbonization process of the European electricity sector. Its scope is also broadly consistent with major international energy statistics, such as those from Eurostat and the IEA.

2.2 Variables and Definitions

The indicators in the dataset are classified according to the category–subcategory–variable–unit hierarchy. The main variables used in the study are outlined below.

- Clean (%) : Represents the share of renewable energy sources (wind, solar, hydro, biomass) and nuclear energy in total electricity generation.
- Fossil (%) : Refers to the share of electricity generated from coal, natural gas, and other fossil fuels in total generation.
- Wind and Solar (%) : Denotes the combined share of variable renewable sources, wind and solar, in electricity generation.
- Electricity Demand (TWh) : Measures total monthly electricity consumption, calculated as the sum of domestic production and net imports.
- CO₂ Intensity (gCO₂/kWh) : Represents the carbon emission intensity per unit of electricity generated.

During the annualization process, the arithmetic average of monthly values was taken for ratio variables (e.g., Clean and Fossil), while for energy flow variables (e.g., Demand), monthly totals were summed annually. This method reflects annual trends in ratios and ensures the integrity of energy consumption and emissions data on an annual scale. Table 1 summarizes the variables and their corresponding units used in the study.

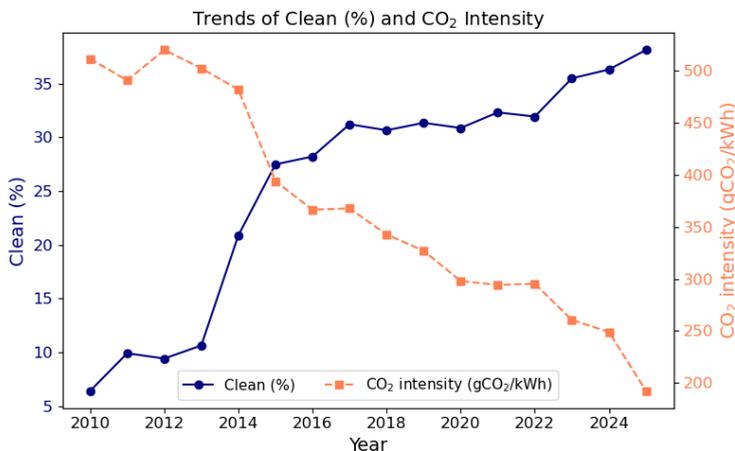
TAB. 1 : Classification of variables by category, subcategory, and unit. **Note** : EG : Electricity Generation, ED : Electricity Demand, EI : Electricity Imports, PSE : Power Sector Emissions.

Category	Subcategory	Variable(s)	Unit(s)
EG	Aggregate fuel	Clean, Fossil, Coal, Wind-Solar, Hydro, Bioenergy, and other renewables, Renewables, Wind	%, TWh
	Fuel	Bioenergy, Gas, Hard coal, Hydro, Onshore wind, Other fossil, Renewables, Other renewables, Solar, Nuclear	%, TWh
	Total	Total generation	TWh
ED	Demand	Demand	TWh
EI	Electricity imports	Net imports	TWh
PSE	Aggregate fuel	Clean, Fossil, Coal, Hydro, bioenergy and other renewables, Renewables, Wind and solar	MtCO ₂ e
	Fuel	Bioenergy, Gas, Hard coal, Hydro, Onshore wind, Other fossil, Other renewables, Solar, Nuclear	MtCO ₂ e
	CO ₂ intensity	CO ₂ intensity	gCO ₂ e per kWh

2.3 Analytical Framework

This study, which aims to assess the decarbonization processes in the European electricity sector systematically, presents a three-stage integrated analytical framework. In the first stage, the key dynamics in the industry are revealed through descriptive statistics and visual analysis. In the second stage, a quantitative analysis of the factors influencing CO₂ intensity (gCO₂/kWh) uses a fixed-effects panel model. In the final stage, the structural breaks and deviation trends observed during the 2021-2022 energy crisis are examined in detail. This stepwise approach allows for a comprehensive assessment of the impacts of short-term macroeconomic shocks on the sector and long-term structural trends.

First, the Clean (%), Fossil (%), Wind and Solar (%), Electricity Demand (TWh), and CO₂ Intensity (gCO₂/kWh) indicators for the 2015-2024 period were converted to annual data. Annualization was performed by taking the arithmetic average of monthly observations for the share series (Clean, Fossil, Wind, and Solar), and by annual aggregation of monthly totals for the energy quantity series (Electricity Demand). In the next step, the median of the annual series at the country level was calculated and visualized to reflect the central tendency at the European scale. fig. 1 provides a preliminary visual analysis of the relationship between the two variables by showing the time-dependent changes in Clean (%) and CO₂ intensity. As shown in fig. 1, the share of clean energy increased significantly from 2010 to 2024, while CO₂ intensity decreased steadily. This demonstrates that the decarbonization process in the electricity sector is progressing successfully.

FIG. 1 : Trends of clean (%) and CO₂ intensity

In the second stage, we estimate a panel regression model to analyze the determinants of CO₂ intensity (gCO₂/kWh), using an annualized dataset. The model includes country and year fixed effects to control for time-invariant heterogeneity and standard temporal shocks. The main independent variables are the shares of clean, wind, and solar energy (%). The logarithm of electricity demand ($\log(\text{Demand})$) is included as a control variable. The results are presented in Section 3.

The third stage investigates structural deviations in the relationship between renewable energy share and carbon intensity during the 2021-2022 energy crisis. For this purpose, a crisis dummy variable is defined as $\text{Crisis} = 1$ if $\text{Year} \in \{2021, 2022\}$, and its interaction with the clean energy share ($\text{Clean}\%$) is included in the model. The CO₂ intensity distributions for the pre-crisis, crisis, and post-crisis periods are presented as box plots in fig. 2. fig. 2 shows that the crisis period marked a notable reversal in the decarbonization trend of the European electricity sector. The distribution of CO₂ intensity, which remained relatively high and stable during the pre-crisis period (2015-2020), showed a significant shift during the crisis. While a slight increase in the median value was observed during the crisis, the widening distribution suggests heterogeneous responses across countries. However, the most pronounced development emerged in the post-crisis period of 2023-2024. The median CO₂ intensity decreased by approximately 60% to 150 gCO₂/kWh, indicating a structural transformation in the sector. The narrowing of the distribution and the reduction of outliers indicate that this improvement is widespread and systematic. These findings suggest that, despite the short-term negative impacts of the energy crisis, the decarbonization process of the electricity sector accelerated in the medium term.

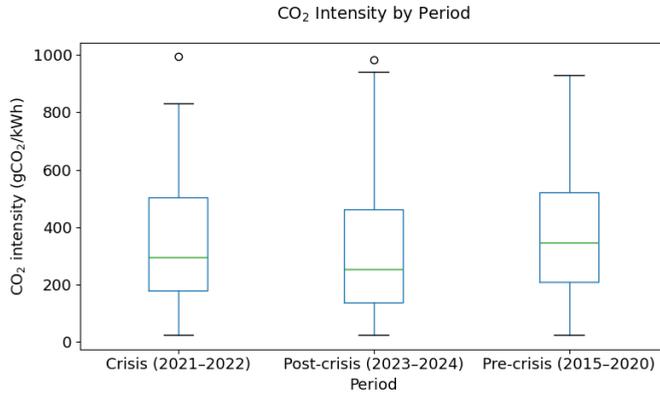


FIG. 2 : CO₂ intensity by period : Pre-crisis (2015–2020), Crisis (2021–2022), Post-crisis (2023–2024)

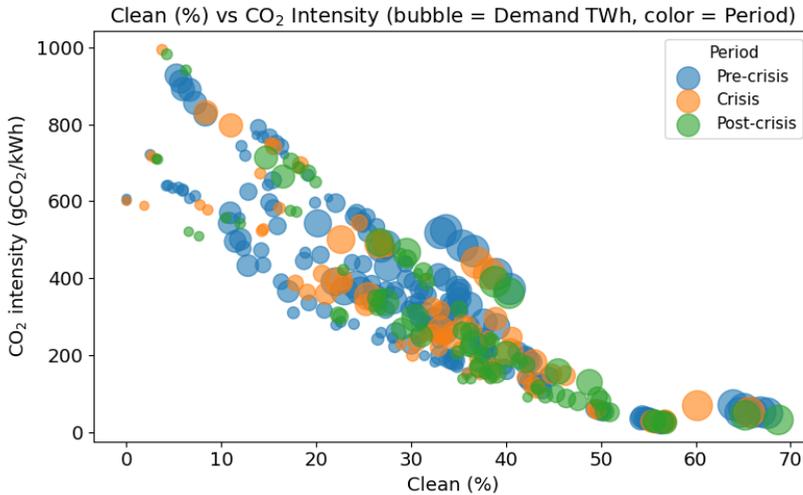


FIG. 3 : Clean (%) vs CO₂ intensity with demand bubbles and period coloring (annual, country level).

To visualize the conditional impact of the crisis period on the mix-intensity relationship, fig. 3 presents the relationship between Clean (%) and CO₂ intensity, scaled by demand (TWh) and color-coded by period. This scatterplot allows visual analysis of whether carbon intensity systematically changed in countries with similar clean energy shares during the crisis. While the distribution in fig. 3 confirms the expected negative relationship between clean energy share and carbon intensity, it also reveals significant deviations specific to the crisis period. While the distribution followed a relatively narrow band in the pre-crisis period (blue dots), it is noteworthy that CO₂ intensity deviated upwards during the crisis period (orange dots), particularly in the 30-50% clean energy share range. This indicates that during the energy

crisis, the existing capacity of clean energy resources had to be supplemented with higher carbon-intensity resources. In the post-crisis period (green dots), the distribution reconsolidated, shifting generally to lower intensity values. Bubble sizes scaled to demand show that large economies cluster around the center of the distribution, whereas smaller economies are more dispersed.

3 Results and Discussion

3.1 Descriptive Statistics

The annual panel dataset used in the study covers 2015–2024, and descriptive statistics for the main variables are presented in Table 2. The table summarizes measures of central tendency and dispersion for the variables Clean (%), Wind–Solar (%), Electricity demand (TWh), $\log(\text{Demand})$, and CO₂ intensity (gCO₂/kWh). Descriptive statistics indicate significant heterogeneity in the clean energy transition processes among European countries : The average Clean share is 30.55%, the standard deviation is 14.66, and the values range from zero to 68.73, indicating that countries are at different stages of the energy transition. Furthermore, the average wind and solar share is 9.31%, suggesting that a significant portion of clean energy comes from other sources such as hydropower and nuclear power. The range in electricity demand, with a standard deviation of 129.61 and ranging from 1.44 TWh to 551.93 TWh, reflects significant differences in the economic scales of countries. In addition, the demand variable in logarithmic form shows an average value of 3.80 with a standard deviation of 1.41, highlighting the skewed distribution of electricity demand across countries. The standard deviation of 221.71 and the interquartile range of 184.40–505.86 in CO₂ intensity indicate substantial structural differences across electricity generation mixes.

TAB. 2 : Descriptive statistics of main variables (annual panel, 2015–2024).

	Mean	Std	Min	25%	50%	75%	Max
Clean (%)	30.55	14.66	0	20.17	31.30	38.39	68.73
Wind-Solar (%)	9.31	8.27	0	2.63	6.95	13.6	36.47
Demand (TWh)	102.29	129.61	1.44	12.8	48.99	131.55	551.93
$\log(\text{Demand})$	3.80	1.41	0.36	2.55	3.89	4.88	6.31
CO ₂ intensity	354.38	221.71	23.6	184.4	325.07	505.86	993.81

3.2 Panel Data Regression Analysis

A fixed-effects panel data regression model was applied at the country-year level to examine the determinants of decarbonization trends in the electricity sector. CO₂ intensity (gCO₂/kWh) was used as the dependent variable, and clean (%), wind, and solar (%) were included as the main independent variables. The $\log(\text{Demand})$ variable, measured in TWh, was added to the model to control the scale effect of electricity demand. The model can be defined as follows :

$$Y_{i,t} = \alpha + \beta_1 X_{i,t}^{(WS)} + \beta_2 X_{i,t}^{(OC)} + \beta_3 X_{i,t}^{(D)} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (1)$$

where $Y_{i,t}$ denotes the carbon intensity for country i at time t ; $X_{i,t}^{(WS)}$ represents the share of wind and solar (WS) power in electricity generation; $X_{i,t}^{(OC)}$ denotes the share of other clean (OC) energy sources (calculated as total clean energy minus wind and solar, primarily including hydro and nuclear power); $X_{i,t}^{(D)}$ is electricity demand (D) expressed in logarithmic form; μ_i captures country-specific fixed effects; λ_t captures time-specific fixed effects; and $\varepsilon_{i,t}$ is the error term.

Table 3 presents the coefficient estimates from the fixed effects panel regression. The model incorporates country- and year-fixed effects and is based on 335 observations covering 2015–2024. The within R^2 is 0.822, indicating that the explanatory variables explain a large proportion of the variation in CO_2 intensity after controlling for unobserved heterogeneity across countries and years. The coefficient for wind and solar (%) is -12.18 ($p < 0.01$), negative and highly significant. This implies that a 1% increase in the share of wind and solar power is associated with an average reduction of about 12 units in CO_2 intensity. Similarly, the coefficient for other clean (%) is -12.24 ($p < 0.01$), also negative and highly significant, suggesting that hydro, nuclear, and other clean sources contribute comparably to the reduction in CO_2 intensity. In contrast, the coefficient for $\log(\text{Demand})$ is -1.99 ($p \approx 0.79$), which is negative and statistically not significant (ns), indicating that electricity demand does not have a measurable impact on CO_2 intensity in this specification.

TAB. 3 : Fixed effects panel regression results (2015–2024). Notes : *** ($p < 0.01$), ** ($p < 0.05$), * ($p < 0.1$), ns = not significant. Electricity demand measured in TWh.

Variable	Coefficient (β)	Std. Error	t-statistic	Significance
Wind and solar (%)	-12.183	1.359	-8.962	***
Clean (%)	-12.237	1.668	-7.333	***
$\log(\text{Demand})$	-1.985	7.452	-0.266	ns

fig.4 presents the coefficient estimates and their 95% confidence intervals derived from the panel regression analysis. The wind and solar variable exhibits a statistically significant negative coefficient of approximately -12 , indicating that a 1% increase in the share of wind and solar power is associated with a reduction in CO_2 intensity of about 12 gCO_2/kWh . The confidence interval remains entirely below zero, confirming the robustness of this relationship. Similarly, the Other clean coefficient is estimated at approximately -12 and is statistically significant, suggesting that hydro, nuclear, and other clean sources contribute comparably to reducing CO_2 intensity. Finally, the $\log(\text{Demand})$ coefficient, while slightly negative at around -2 , displays a wide confidence interval that spans both negative and positive values. This pattern indicates that electricity demand does not exert a statistically significant or economically meaningful influence on CO_2 intensity in the estimated model.

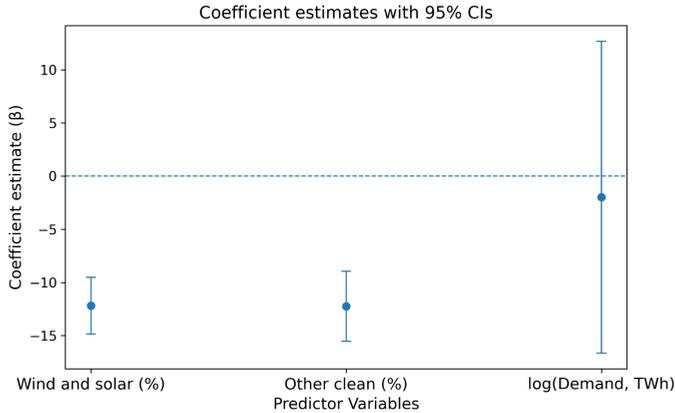


FIG. 4 : Coefficient plot of panel regression

3.3 Crisis Period Analysis

An energy crisis in the European electricity sector marked 2021–2022. Natural gas supply constraints, price shocks, and the effects of the Russo-Ukrainian war led to a resurgence of coal use in many countries, resulting in temporary yet significant increases in carbon intensity. Therefore, a Crisis dummy and a Clean × Crisis interaction term were added to the model to test whether the relationship between the energy mix and carbon intensity changed during the crisis period. The estimated model can be specified as follows :

$$Y_{i,t} = \alpha + \beta_1 X_{i,t}^{(WS)} + \beta_2 X_{i,t}^{(OC)} + \beta_3 X_{i,t}^{(D)} + \beta_4 Z_t + \delta_1 (X_{i,t}^{(WS)} \times Z_t) + \delta_2 (X_{i,t}^{(OC)} \times Z_t) + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (2)$$

where Z_t is a crisis dummy, equal to 1 for crisis years (2021–2022) and zero otherwise. The interaction term $X_{i,t}^{(WS)} \times Z_t$ and $X_{i,t}^{(OC)} \times Z_t$ capture whether the effects of wind–solar and other clean energy on CO₂. The coefficients β_1 and β_2 represent the baseline effects of wind–solar, and other clean energy sources on CO₂ intensity in non-crisis periods, while δ_1 and δ_2 measure the extent to which these effects change under crisis conditions.

Table 4 reports the regression results incorporating the crisis interaction. The estimation relies on 335 observations for 2015–2024 and accounts for both country- and year-fixed effects. The within R² of 0.816 indicates that the model explains a substantial proportion of the variation in CO₂ intensity after controlling for unobserved heterogeneity. The results show that both wind–solar and other clean energy shares exert a statistically significant adverse effect on CO₂ intensity, with coefficients of -12.17 (p < 0.01) and -12.22 (p < 0.01), respectively. This finding provides strong evidence that increasing the contribution of clean energy sources is systematically associated with reductions in carbon intensity. In contrast, electricity demand in logarithmic form shows no significant effect on CO₂ intensity ($\beta = -1.76$, p ≈ 0.81).

The interaction terms between clean energy and the crisis period are statistically insignificant, suggesting that the marginal effects of wind–solar, and other clean energy on CO₂ intensity did not change appreciably during the crisis years 2021–2022.

TABLE 4 : Fixed effects panel regression results with crisis interaction. **Notes** : *** ($p < 0.01$), ** ($p < 0.05$), * ($p < 0.1$), ns = not significant. Electricity demand measured in TWh.

Variable	Coefficient (β)	Std. Error	t-statistic	Significance
Other clean (%)	-12.223	1.679	-7.276	***
Wind and solar (%)	-12.173	1.348	-9.029	***
log(Demand)	-1.761	7.450	-0.236	ns
Wind and solar \times Crisis	0.158	0.436	0.362	ns
Other Clean \times Crisis	0.140	0.253	0.554	ns

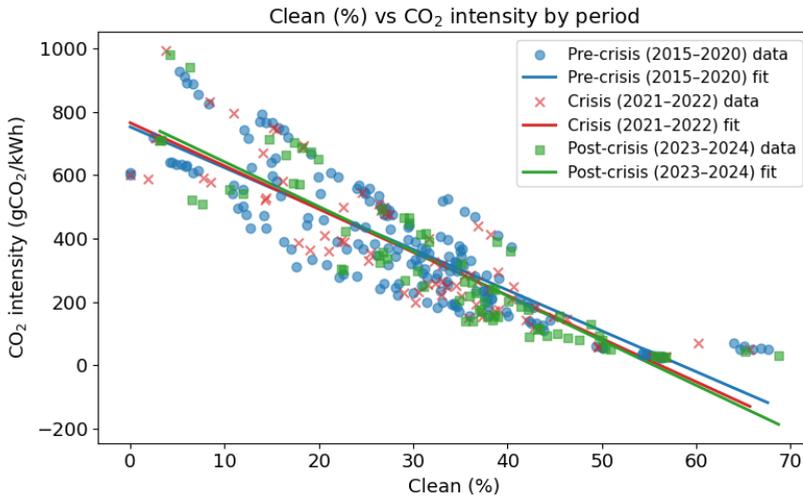


FIG. 5 : Clean energy share and CO₂ intensity across pre-crisis, crisis, and post-crisis periods.

fig. 5 illustrates the relationship between the share of clean energy and CO₂ intensity across different periods. The fitted regression lines consistently exhibit a negative slope of roughly -12 to -13 gCO₂/kWh per 1% increase in clean energy, in line with the panel regression estimates. During the pre-crisis period (2015–2020), CO₂ intensity is concentrated around 600–800 gCO₂/kWh when clean energy shares are below 10%, but falls below 200 gCO₂/kWh once clean shares exceed 40%. In the crisis years (2021–2022), the regression line remains negative with a slope comparable to the pre-crisis trend, but is shifted upward, indicating higher CO₂ intensity levels at similar clean shares. For instance, crisis-period intensity is higher at around 30% clean energy than the pre-crisis benchmark. In the post-crisis period (2023–2024), the fitted line realigns more closely with the pre-crisis trajectory, with CO₂ intensity approaching 200 gCO₂/kWh at clean shares above 40%. Overall, fig. 5 shows that although the crisis years were associated with an upward shift in carbon intensity, the marginal

mitigating effect of clean energy on emissions, reflected in the stable slope of the fitted lines, remained unchanged across periods.

3.4 Cross-country heterogeneity

The decarbonization process in the European electricity sector varies significantly across countries. These differences are clearly visible in clean energy shares and carbon intensity values. However, assessing the energy transition solely based on single-year data is insufficient; long-term trends are necessary to understand the impact of policy choices and crisis periods.

In this context, statistical findings for 2015–2024 are presented in Table 5. The data reveal significant differences in countries' clean energy share and carbon intensity indicators. For example, the clean energy share averaged 38% in countries like Sweden and Norway, while carbon intensity remained at only 25.5 gCO₂/kWh and 31.8 gCO₂/kWh, respectively. In contrast, clean energy shares in Kosovo and Poland were relatively low at 3.2% and 6%, respectively, with carbon intensity reaching as high as 972 gCO₂/kWh and 831 gCO₂/kWh. Similarly, in Bulgaria and Serbia, average intensity values were 479 gCO₂/kWh and 734 gCO₂/kWh.

High standard deviation values highlight the different starting points and pace of progress in countries' decarbonization processes. For example, in Germany, carbon intensity fluctuated throughout the period with a standard deviation of 68.2 gCO₂/kWh, while in Portugal, the standard deviation of the clean energy share reached 29%, demonstrating the impact of policies and crises on production structure. Conversely, low standard deviations of carbon intensity in countries like Switzerland and France indicate a stable low-carbon production profile. In conclusion, analyses from 2015 to 2024 demonstrate the heterogeneity of the energy transition in Europe, and the need to develop country-specific, differentiated strategies rather than uniform solutions within policy frameworks.

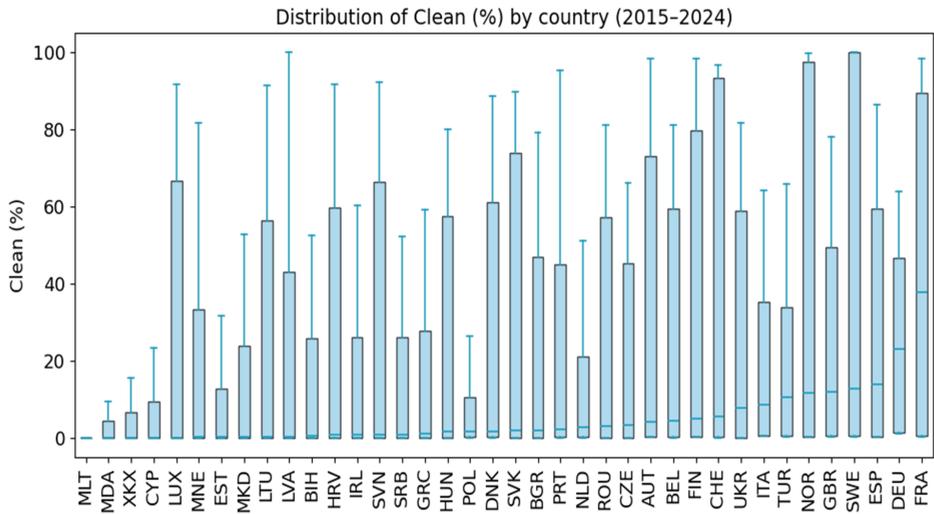
These long-term findings are visually supported by Figs 6(a) and 6(b). fig. 6(a) shows the distribution of clean energy shares in European countries' electricity generation during 2015–2024. Median values remain below 10% in Malta, Moldova, and Kosovo, and around 15% in Poland and Serbia. In contrast, France exhibits a median of 46%, with upper-quartile values approaching 90%. Sweden and Norway record medians of approximately 38% and 37%, respectively, consistent with their low carbon intensity profiles. The box widths reflect intra-period volatility. Spain, Italy, and Germany show broad ranges spanning 10–60%, indicating substantial variation over time, whereas France and Norway display narrower boxes and shorter whiskers, suggesting more stable clean energy shares. Overall, the clean energy share across Europe ranges from near 0% to almost 90%, underscoring the uneven pace of decarbonization.

fig. 6(b) illustrates the distribution of CO₂ intensity in electricity generation across European countries during 2015–2024. The lowest values are observed in Sweden, with a median below 25 gCO₂/kWh, followed by Norway at around 30 gCO₂/kWh and France at 35 gCO₂/kWh. These countries also display narrow interquartile ranges, indicating stable low-carbon production profiles. In contrast, several Eastern and Southeastern European countries exhibit extremely high carbon intensities. Kosovo re-

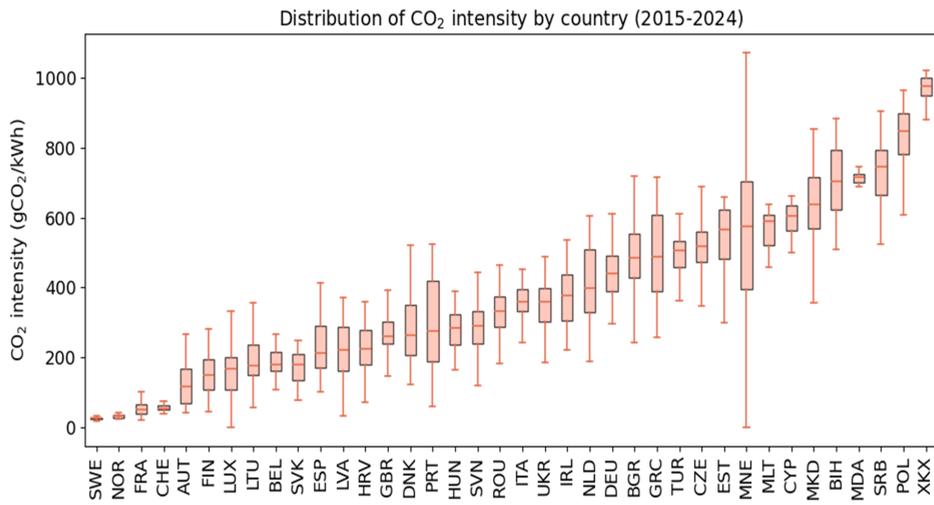
cords a median of about 950 gCO₂/kWh, with values tightly clustered between 900 and 1000 gCO₂/kWh. Poland, Serbia, and Moldova also show high medians in the 650–700 gCO₂/kWh range, far above the EU average. A middle group is found in Western Europe, where Germany (400 gCO₂/kWh), Italy (350 gCO₂/kWh), and the UK (300 gCO₂/kWh) occupy intermediate positions. These countries display broader interquartile ranges, reflecting the effects of coal phase-out and renewable expansion on intra-period variability. Overall, CO₂ intensity across Europe ranges from as low as 20 gCO₂/kWh to nearly 950 gCO₂/kWh, underscoring the unequal pace of decarbonization.

TAB. 5 : Between-country variation in Clean (%) and CO₂ intensity. **Note** : SD = standard deviation

Country	Clean (%)	CO ₂ intensity (CO ₂ /kWh)		
	Mean	SD	Mean	SD
AUT	28.92	38.38	123.31	58.34
BEL	23.12	30.10	189.04	42.54
BGR	18.58	25.53	479.43	103.71
BIH	11.67	17.17	701.34	102.14
CHE	33.37	43.39	55.75	8.77
CYP	4.91	7.78	598.55	42.95
CZE	17.53	22.96	510.51	70.52
DEU	25.24	20.84	438.16	68.20
DNK	23.46	32.68	277.99	92.85
ESP	27.09	29.44	231.09	82.74
EST	8.92	15.59	535.66	102.82
FIN	30.21	39.36	150.04	60.42
FRA	43.73	37.88	52.42	18.89
GBR	22.41	23.92	280.57	71.52
GRC	12.65	18.04	491.26	124.33
HRV	22.78	32.21	223.79	66.28
HUN	21.54	29.63	280.14	57.05
IRL	11.94	17.46	378.07	78.87
ITA	16.88	18.11	359.18	44.94
LTU	21.79	32.17	193.11	67.03
LUX	24.87	35.66	157.78	68.34
LVA	19.64	30.03	219.41	85.98
MDA	1.94	2.95	713.96	15.22
MKD	10.41	15.75	637.78	97.09
MLT	1.79	4.89	571.11	48.42
MNE	16.87	27.59	531.71	257.83
NLD	12.17	16.98	411.43	112.70
NOR	36.82	43.73	31.77	4.76
POL	6.00	8.18	830.76	86.06
PRT	20.37	28.95	293.09	134.61
ROU	21.65	28.79	334.41	62.72
SRB	10.95	15.55	733.53	83.44
SVK	26.70	36.64	170.21	45.48
SVN	24.04	33.82	290.19	89.31
SWE	37.78	44.37	25.46	3.87
TUR	17.25	18.04	493.71	60.65
UKR	23.76	28.58	352.49	63.73
XKX	3.17	4.87	972.11	36.69

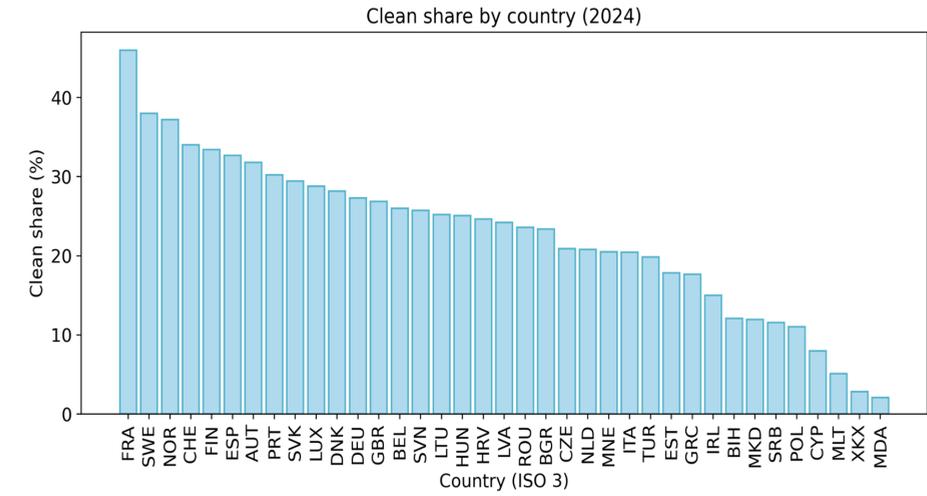


(a)

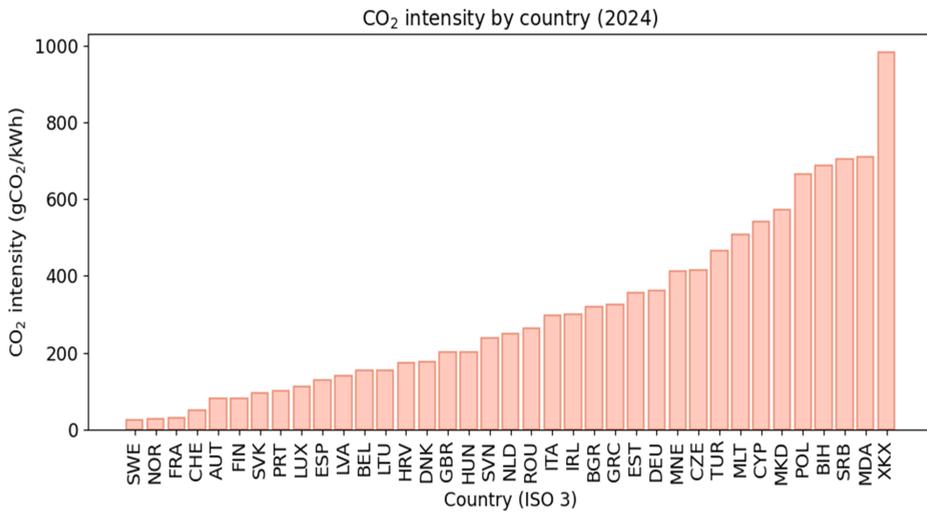


(b)

FIG. 6 : Distribution of Clean (%) and CO₂ intensity across European countries (2015-2024) : (a) Clean (%) (b) CO₂ intensity



(a)



(b)

FIG. 7 : Clean (%) and CO₂ intensity in European countries (2024) : (a) Clean (%) (b) CO₂ intensity

These long-term analyses demonstrate that the energy transition in Europe is structurally heterogeneous. However, the annual country-level values for 2024, calculated as the arithmetic average of monthly observations for each country, reveal the contemporary reflections of this heterogeneity. fig. 7(a) illustrates the distribution of clean energy shares in 2024, showing a wide range across countries. France recorded the highest share at 46%, followed by Sweden at 38% and Norway at 37.2%. At the other end of the spectrum, Kosovo reached only 2.8%, Moldova 2.1%, and Malta 5.1%. Intermediate positions were observed in major electricity producers such as Germany with 27.3%, Spain with 32.7%, and Italy with 20.5%. This distribution confirms that the clean energy transition in Europe is advancing at an uneven pace. fig. 7(b) presents the CO₂ intensities of countries in the same period. Sweden recorded 23.6 gCO₂/kWh, Norway 28.4 gCO₂/kWh, and France 31.2 gCO₂/kWh, all reflecting low-carbon production profiles. At the opposite end, Kosovo reached 982 gCO₂/kWh, Moldova 710 gCO₂/kWh, Poland 664 gCO₂/kWh, and Serbia 704 gCO₂/kWh, standing out with extremely high intensity values. Germany, with 361 gCO₂/kWh, Italy, 296 gCO₂/kWh, and the UK, 201 gCO₂/kWh, represent the intermediate group. This classification indicates that while some countries have made significant progress in adopting low-carbon generation, others remain heavily dependent on carbon-intensive sources. Overall, the 2024 findings confirm substantial heterogeneity in clean energy shares and carbon intensities, underscoring the need to account for country-specific differences when evaluating the energy transition.

3.5 Discussion

The results show that the European electricity sector has achieved notable progress in decarbonization, but this progress is unevenly distributed across countries. The analysis confirms a statistically significant negative relationship between the share of clean energy and CO₂ intensity. The findings suggest that every 1% increase in the share of clean energy is associated with a reduction of approximately 13 gCO₂/kWh in carbon intensity. However, the interaction term added to the model for the 2021–2022 energy crisis indicates a weakening of this effect, suggesting the fragility of energy policies during temporary shifts to fossil fuels.

These findings imply that the rapid emission reduction targets envisaged under the European Green Deal and the Fit for 55 package should be supported by long-term technology investments and mechanisms that enhance system resilience in times of crisis [21]. In this context, the strategies to reduce natural gas dependence highlighted in the REPowerEU plan are particularly important, especially for Eastern and Southern European countries [22].

The heterogeneity between countries is also substantial. According to 2024 data, carbon intensity in countries with high hydroelectric and nuclear capacity, such as Sweden, France, and Norway, is 23.6, 31.2, and 28.4 gCO₂/kWh, respectively, while clean energy shares are in the range of 38–46%. In contrast, in countries with high fossil fuel dependence, such as Poland, Serbia, and Bosnia and Herzegovina, carbon intensity exceeds 650 gCO₂/kWh, whereas the clean energy share remains below 12%. These differences underscore the limitations of uniform policies and point to the need for differentiated country-based strategies. In countries with high carbon intensity, po-

licy efforts may need to focus on accelerating the coal phase-out through financial support and infrastructure transformation, while in countries with low carbon intensity, renewable energy integration should be reinforced with policies that enhance system resilience. The findings are consistent with existing studies that emphasize the importance of policy differentiation in the European energy transition [23–25].

Finally, managing the growth in electricity demand remains a key issue. While the demand coefficient in the models is not statistically significant in all equations, descriptive findings suggest that the increase in demand is mainly met by fossil fuel generation. Therefore, addressing this growing demand in line with the decarbonization process requires renewable investments and comprehensive policies promoting energy efficiency, storage technologies, and grid modernization.

Overall, the policy debate highlights three main insights :

- *Resilience* : Flexible energy security policies are essential to avoid reliance on fossil fuels during times of crisis.
- *Targeted support* : Cross-country differences suggest strategies tailored to specific starting points and policy priorities.
- *Holistic approach* : Decarbonization is unlikely to be sustained unless grid modernization and energy efficiency policies complement renewable investments.

4 Conclusion

This study provides a comprehensive analysis of the decarbonization process in the European electricity sector over the period 2015–2024, focusing on clean energy shares, carbon intensity, and the effects of crisis periods using panel data. Descriptive statistics and regression results show that progress across Europe varies significantly across countries. Fluctuations during the 2021–2022 energy crisis highlighted the vulnerabilities of the decarbonization process, while the results also confirm the long-term benefits of clean energy investments. In this context, the study identifies general trends and country-specific variations with implications for policy design. Based on these findings, four key conclusions can be drawn :

- *The impact of the clean energy share* : The panel regression analysis provides a disaggregated assessment of clean energy sources. The results indicate that a 1% increase in the share of wind and solar is associated with an average reduction of 12.18 gCO₂/kWh ($p < 0.01$). In addition, a 1% increase in the share of other clean sources, including hydro, nuclear, and other low-carbon technologies, is associated with a reduction of 12.24 gCO₂/kWh ($p < 0.01$). These results highlight that all clean energy components make comparably strong and statistically significant contributions to reducing carbon intensity.
- *The impact of the energy crisis* : The regression results with crisis interactions indicate that the mitigating effects of both clean energy components on CO₂ intensity persisted during the crisis period (Wind–solar : $\beta = -12.17$, $p < 0.01$; Other clean : $\beta = -12.22$, $p < 0.01$). Electricity demand (log) remains statistically insignificant ($\beta = -1.76$, $p \approx 0.81$). The terms of crisis interaction are also

negligible, suggesting that the marginal effect of clean energy did not change meaningfully between 2021 and 2022.

- *Cross-country heterogeneity* : The 2024 data confirm the uneven profile of decarbonization. Sweden (23.6 gCO₂/kWh, Clean 38%), France (31.2 gCO₂/kWh, Clean 46%) and Norway (28.4 gCO₂/kWh, Clean 37%) stand out among low-carbon countries, while Poland (664 gCO₂/kWh, Clean 11%), Serbia (704 gCO₂/kWh, Clean 12%) and Kosovo (982 gCO₂/kWh, Clean 3%) stand out with their high-carbon profiles.

Overall, the study shows that the European electricity sector has made significant progress in decarbonization, but fossil fuel dependence can resurface during times of crisis. Furthermore, the substantial variations observed across countries suggest that focusing on average trends at the European level can be misleading and that differentiated approaches to policy design are essential.

Authorship contribution statement

Murat Uyar : Methodology, Software, Validation, Writing–original draft, Writing–review & editing. Şekip Esat Hayber : Conceptualization, Validation, Formal analysis, Investigation, Writing–review & editing.

Conflicts of Interest

The authors declare no conflict of interest.

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