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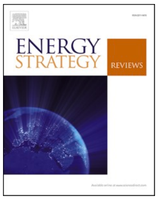

Dynamic effect of disaggregated level electricity generation on residential carbon emissions: Daily inference from the largest EU economies

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ABSTRACT

This study examines the dynamic effects of electricity generation (EG) on CO_2 emissions from the residential sector. The study focuses on the EU-4 countries (Germany, Spain, France, and Italy), considers residential CO_2 emissions as the dependent variable, and includes disaggregated level fossil and renewable EG as explanatory variables. In this context, the study runs nonlinear quantile-on-quantile (QQ) regression and Granger causality in quantiles (GQ) as the main models with daily data from January 2, 2019, to March 10, 2023, while quantile regression (QR) is used for robustness check. The findings present that in terms of CO_2 emissions: (i) EG from coal, natural gas, and oil has a stimulating effect at higher quantiles in all countries; (ii) EG from hydro has an increasing effect at higher quantiles, while it has a decreasing effect at lower and middle quantiles in all countries except France; (iii) EG from solar has a dampening effect at higher quantiles in all countries except France; (iv) EG from wind has a declining effect at higher quantiles in both Spain and France; (v) both fossil and renewable energy EG have a causal effect on residential sector CO_2 emissions at the disaggregated level except at some quantiles. Overall, the effect size and the causal effect of EG on CO_2 emissions change for quantiles, countries, and EG sources. Therefore, the study proposes to rely on the specific EG sources for Germany and Italy (solar energy), Spain, and France (wind energy) to mitigate climate change by reducing residential CO_2 emissions.

1. Introduction

Energy is recognized worldwide as an important factor of production, and energy is on the political agenda of countries as an important strategic element with economic and environmental implications. Although in the past countries have pursued a growth strategy dependent on fossil fuels, today there is a trend toward renewable energy sources. The use of renewable resources has benefits such as reducing CO_2 emissions, improving the environment, reducing fuel consumption, and supplementing with clean energy [1]. As renewable energy is sustainable, environmentally friendly, and carbon-neutral, this type of energy plays an important role in achieving the 2 °C goals of the Paris Agreement [2]. Especially after the 1973 oil crisis and the subsequent high oil prices, the development of renewable energy systems has become widespread [3].

Fuels such as coal and oil are high carbon polluters. Widely used in the transportation and industrial sectors, these energy sources cause global warming problems by increasing CO_2 emissions. In fact, in addition to environmental damage, the use of fossil fuels also causes direct damage to people's brains [4]. The burning of fossil fuels is causing a crisis comparable to air pollution, as it expands the release of many harmful gasses, which negatively affects human health [5]. Countries and international organizations are striving to minimize these harmful effects and provide better environmental conditions for societies. At this point, it is an important research topic to determine which fossil fuel increases CO_2 emissions by how much and to what extent EG

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from energy sources such as solar and wind power mitigates CO_2 emissions to prevent this increase. This study focuses on the relevant research topic for four EU countries. EU countries are at the forefront of carbon reduction measures and have positioned themselves as international leaders in the development of climate-related energy policies [6]. EU countries are leading the way in promoting the development of technologies that reduce CO_2 emissions [7]. The fact that EU countries steer global climate policy has made the reduction of CO_2 emissions a priority in these countries.

CO_2 emissions originate from various sectors such as transport, industry, agriculture, and residential. EU countries are striving to reduce residential CO_2 emissions by raising clean awareness among their citizens. There is a clear link between the introduction of renewable energy in the electricity sector and CO_2 reduction through the substitution of carbon-based systems [8]. As the electricity sector can be decarbonized faster than other sectors [9], residential CO_2 emissions can be reduced through regulations in this sector. To this end, EU countries have sought to promote EG from renewable resources with legislation such as Directive 2001/77/EC and Directive 2009/28/EC. With the Renewable Energy Directive of 2018, the EU has declared that it aims to provide 32% of its energy supply from renewable sources by 2030 [10].

The EU's incentives for EG from renewable energy sources have had some success. The latest European Commission [11] report shows that electricity from renewable sources now accounts for the largest share of total EG, around 38%, compared to 36% from fossil fuels. There has been significant growth in the renewable energy sector, with increasing investment in wind, solar, and hydropower in the EU. For example, EG from wind and solar power has increased from 8% to 19% in the last ten years, between 2011 and 2021, making it the fastest-growing renewable energy source compared to nuclear and hydropower [12].

All EU countries listed in Appendix-1 of the Kyoto Protocol have introduced alternative renewable energy strategies to reduce CO_2 emissions. In addition, EU countries have also signed the Paris Agreement, and EU countries such as Germany and France have recently taken the lead in reducing CO_2 emissions. EU countries are key players in reducing global GHG emissions and have committed to creating a 100% clean or zero-emission economy by 2050 [13]. For many years, the EU has been pursuing a carbon removal policy and has created various incentive schemes to reduce the use of coal in the heating and energy sector [14]. Due to the volatility of oil and energy prices and environmental concerns, EU policy aims to promote renewable energy, and the EU strategy aims to reduce energy outages and problems in the electricity grid by increasing electricity interconnection for member states [15]. Minimizing carbon in EG in EU countries is of global importance. The ability of EU countries to reduce the carbon intensity of EG is a prerequisite for a sustainable global order and the achievement of climate targets. In this context, EU countries are increasing their investments in renewable energy.

In the EU, the residential sector accounts for 27% of total energy consumption, 24.6% of which is electricity consumption [16]. A quarter of the electricity produced and consumed in EU countries comes from the residential sector. In this context, residential sector electrical energy has great potential to reduce consumption-related CO_2 emissions [17]. According to Wang et al. [13], EU countries should increase the share of clean energy in their energy portfolio to meet the 2019 European Green Deal targets. Azevedo et al. [18] found that electricity prices in EU countries are not flexible and that a 10% price increase only reduces CO_2 emissions by 2%, so the residential sector needs energy savings and the use of more energy-efficient technologies in electricity consumption to combat climate change. In this context, investigating the effectiveness of renewable energy in reducing CO_2 emissions from the residential sector is an important issue.

Based on the above information, this study examines the effectiveness of renewable EG in reducing CO_2 emissions from the residential sector in EU countries. In this context, the study makes various contributions to the literature (i) In contrast to previous studies, this study is the first to analyze the relationships between daily CO_2 emissions of the residential sector and daily EG from renewable energy sources for EU countries; (ii) The study comparatively analyzes which type of renewable energy is effective in reducing residential CO_2 emissions for which EU country; (iii) The study compares and discusses in detail the impact of fossil and renewable EG on residential CO_2 emissions with daily data. In summary, by taking a sectoral approach, using daily data, applying the current quantile-based methodology, and including disaggregated energy variables, the study provides a different perspective for assessing the EU's 2050 net-zero targets.

The motivation of the study is to examine the economic and environmental impact of energy in the EU countries following the Russia-Ukraine crisis. With the Russia-Ukraine crisis and the subsequent process, EU countries are discussing alternatives to natural gas. These alternatives have different economic and environmental impacts. In this context, the study analyzes for the first time the impact of daily EG from renewables on daily residential CO_2 emissions. What distinguishes the study from previous studies is that there is no previous study in the literature that analyzes daily data for EU countries considering sectoral and disaggregated EG. The study aims to answer the question of whether solar or wind electricity is more effective in reducing daily residential CO_2 emissions in EU countries. The main findings of the study indicate that EG with solar energy for Germany and Italy, and wind energy for Spain and France is suitable to reduce residential CO_2 emissions.

The study consists of further parts. It consists of the presentation of a theoretical framework and a review of the empirical literature in Section 2, empirical process explanations in Section 3, a presentation of the empirical results in Section 4, and a summary of the study along with discussion, policy implications, limitations, and future research in Section 5.

2. Theoretical framework and literature review

2.1. Theoretical background

The Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model by Dietz and Rosa [19] and York et al. [20] shows that population, technology, affluence and energy consumption are important determinants of environmental degradation [21]. STIRPAT incorporates many sociological factors into the empirical model and theoretically analyzes their environmental impacts. In this context, many studies have found that energy consumption and economic growth have a significant impact on CO_2 emissions under STIRPAT (see e.g., Ref. [22,23]).

Moreover, according to Grossman & Krueger [24], economic growth accelerates environmental pollution through the scale effect. Energy, as a factor of production, supports economic growth, but the use of fossil fuels during the growth process leads to irreversible environmental damage. In this context, renewable energy sources can mitigate and decouple the close relationship between economic growth and CO_2 emissions, even though environmental economic theories do not emphasize the role of low-carbon energy [25]. In other words, renewable EG can help reduce environmental degradation. At this point, what type of renewable energy should be promoted for EG is important for economic and environmental efficiency. Therefore, this study examines the environmental efficiency of renewable resources in EG production in EU countries, taking into account the relevant theoretical foundations in the field of energy and environment.

2.2. Review of the empirical studies

The world has been confronted with serious environmental problems in recent decades. Most climate-related problems, such as increasing air pollution and emissions, are due to mankind's anthropogenic activities [26,27]. According to Our World in Data [28], World Bank [29], and Energy Institute [30], which report on total GHG emissions, total CO_2

emissions, and CO_2 emissions from energy use, most greenhouse gas emissions consist of CO_2 emissions and high amount of energy use is the main cause of CO_2 emissions, which account for about 98% of total CO_2 emissions.

Public interest in the relationship between energy and the environment has increased as high economic growth and high energy use lead to significantly higher CO_2 emissions [31,32]. In this context, some studies have focused on the impact of energy prices, energy efficiency, and carbon market on the environment [33–38]. Moreover, various studies have empirically analyzed the relationship between different types of energy use and CO_2 emissions. In this context, one group of studies has focused on the impact of traditional energies on the environment [39, 40], while much more recent studies have focused on the impact of clean energies on the environment [41,42]. While these studies have determined a link between energy use and the environment (intensively proxied by CO_2 emissions), the impact of total energy use as well as each type of energy is different at a disaggregated level, leading to mixed results. Therefore, new empirical studies are needed to clarify the environmental impact of energy use at a disaggregated level.

Another reason why EU countries are questioning the economic and environmental impact of renewable energy is the Russia-Ukraine crisis. The EU has been facing an energy crisis recently, mainly due to the conflict between Russia and Ukraine [43]. Various reciprocal sanctions have been imposed between the EU and Russia and, as a countermeasure, Russia has reduced natural gas supplies to EU countries. In this context, evaluation of alternative energy sources is highly needed [44]. Among the alternatives, some countries, such as Germany, prefer to rely on further coal energy use [45], while other countries are looking for other ways. Therefore, it is crucial to consider the environmental impacts of choosing alternative energy sources for power generation (i.e., electricity). Taking these points into account, the study aims to analyze the dynamic relationship between electricity generation from different sources and residential CO_2 emissions, which are highly vulnerable to electricity outages, in a detailed empirical approach.

Some studies have addressed the consideration of CO_2 emissions at a disaggregated level in empirical analyses by examining several aspects of residential CO_2 emissions ($RSCO_2$). Among these studies, reviews have provided broader coverage of the patterns of drivers of $RSCO_2$. For instance, Zhang & Wang [46] review 144 countries and determine that high (lower) income countries should focus on demand (supply) side policies to mitigate $RSCO_2$. Similarly, Zeng et al. [47] review the studies conducted from 1993 to 2019 that specifically address the patterns of $RSCO_2$ and find that research on $RSCO_2$ is rapidly increasing, with the United States and China playing a dominant role.

Li et al. [48] determine that urban $RSCO_2$ is higher than rural $RSCO_2$ in China and that urbanization is a factor that increases $RSCO_2$. Yang and Liu [49] employ a social practice model to investigate the relationship between CO_2 emissions and daily residential energy consumption in several cities. The result shows an uneven distribution of urban $RSCO_2$, largely due to differences in economic characteristics (e.g., income level, lifestyle, asset ownership) across the regions, while space heating is associated with the most CO_2 emissions from daily energy utilization in the northern region. Langevin et al. [50] report that renewable energy penetration and electrification can reduce CO_2 emissions in the United States by nearly 70%. Liu et al. [51] conduct various panel data estimation methods and conclude that China should switch its residential energy consumption to renewable energy to reduce CO_2 emissions. By observing Chinese rural and urban areas in 30 provinces, Fan et al. [52] investigated the role of population aging on $RSCO_2$. The results of threshold regression show that the aging of the urban population deteriorates environmental quality by increasing $RSCO_2$.

In addition, the role of the energy mix on residential environmental indicators has also been investigated in the literature [53,54]. Using the suburban region of Chittagong in Bangladesh as an example, Baul et al. [53] examine the impact of biomass and conventional energy sources on $RSCO_2$ and the results show that $RSCO_2$ is largely based on biomass (87% of total monthly energy). Similarly, Zhu et al. [54] use a spatial regression approach for 29 Chinese provinces and reveal that $RSCO_2$ in rural areas is reduced by the increased use of biogas plants and solar water heating systems.

2.3. *Evaluation of the literature*

Although some of the studies mentioned above address the relationship between CO_2 emissions from the residential sector and energy consumption, there are notable gaps in the existing literature. For instance, there are few studies on the relationship between the main energy sources (e.g., coal, natural gas, fossil oil, hydro, solar, wind) and $RSCO_2$. Apart from the limited use of econometric approaches in the literature on this topic, there is no utilization of daily datasets for the largest EU countries. Also, novel quantile-based methods have rarely been used to study $RSCO_2$.

The current approach therefore exploits this existing gap to make a further important contribution to the literature on the drivers of $RSCO_2$ by using high-frequency (daily) data, performing novel nonlinear quantile-based approaches, and examining the leading EU-4 countries. Therefore, this study extends the literature by filling the defined gap.

3. Methods

3.1. *Data*

The four leading European countries (Germany, Spain, France, and Italy) form the scope of the study. This study therefore examines the effect of EG on residential CO_2 emissions at a disaggregated level. In this context, the study uses high-frequency (i.e., daily) data between January 2, 2019 and March 10, 2023. Since data are not available for some indicators at other points in time, these data have been excluded from the dataset. Based on data availability, the dataset includes 1527 observations.

The study uses the log-difference daily data series for both the disaggregated level EG and the CO_2 emissions, which is gathered from Carbonmonitor [55]. Table 1 presents the details of the variables.

3.2. *Empirical methodology*

Fig. 1 presents the conceptual framework followed up in the empirical analysis. The proposed methodology includes seven fundamental steps that have been carefully elaborated to advance the exploration of the research objectives and facilitate the study of the relationships among the variables.

The empirical process begins with a critical first step dedicated to data collection, which involves synthesizing relevant information from two separate sources. The second and third parts of the approach include a preliminary analysis, which is essential for understanding the data obtained and the variables under inquiry. The study includes the calculation of descriptive statistics, which provide a succinct yet complete description of the basic characteristics and distributional properties of the variables. Correlation analysis is also used to examine the associations and dependencies of the variables to gain insight into their

Table 1
Variable definitions.

Variable	Definition	Unit	Source
CO_2	Residential CO_2 Emissions	Metric Ton/Day	Carbonmonitor [55]
COAL	EG from Coal	Gigawatt-Hour/ Day	Carbonmonitor [55]
GAS	EG from Natural Gas		
OIL	EG from Oil		
HYDRO	EG from Hydro		
SOLAR	EG from Solar		
WIND	EG from Wind		

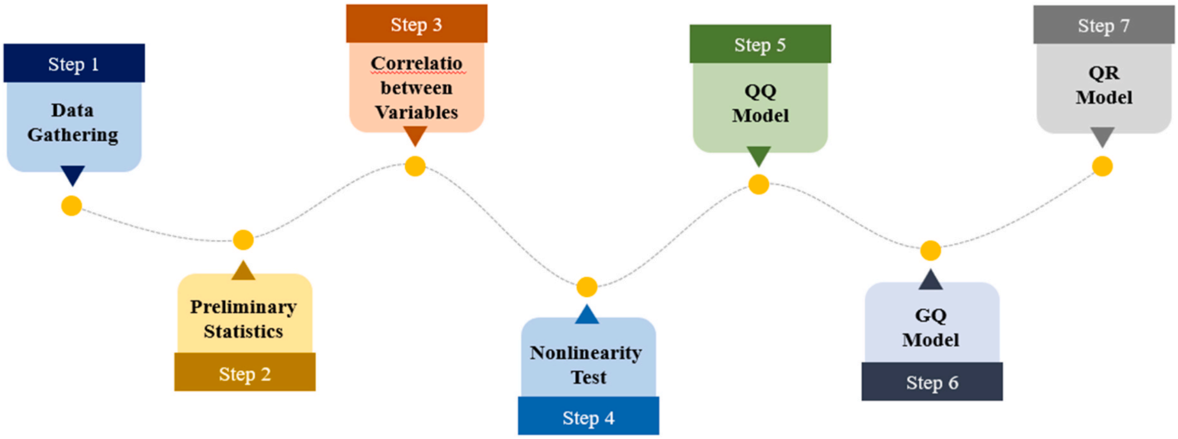


Fig. 1. The conceptual framework of methodology.

interactions within the dataset. A thorough normality test is conducted to evaluate the assumption of normal distribution, as this has substantial consequences for many statistical studies.

The fourth stage of the technique focuses on verifying the basic assumptions underpinning the dataset to ensure the validity of subsequent studies. In this context, the assessment of nonlinearity, specifically the BDS test [56], is crucial to determine the presence and strength of linear correlations between variables. By analyzing nonlinearity, researchers can determine whether the use of linear models is appropriate.

In the fifth and sixth phases, the QQ and GQ techniques are used to examine quantile-based effects and causality. The QQ technique departs from the traditional mean-based approaches by examining in more detail the subtle relationships at different quantiles or specific locations within the distribution. Because it assesses the relationships specific to each quantile, this technique provides a more accurate picture of how the variables in different parts of the distribution are related. The GQ procedure, on the other hand, goes beyond mean effects to investigate causal linkages at different quantiles of the distribution. In contrast to typical causality measures such as correlation or regression, the GQ method provides insights into quantile-based causality, which increases the depth of research [57].

Lastly, the study employs the QR analysis to confirm and strengthen the conclusions obtained by the QQ and GQ methods. The study intends to guarantee the reliability, robustness, and generalizability of the results obtained by including the QR analysis as an extra verification tool. QR analysis provides a robustness check that contributes to the overall rigor of the study and increases confidence in the results [58].

3.3. Econometric models

3.3.1. QQ model

To assess the relationship among variables in the lower, middle, and upper quantiles, the QQ approach [59] is applied. This approach captures the effects of different quantiles of the explanatory variable on distinct quantiles of the dependent variable. Moreover, unlike ordinary least squares and QR methods, it takes into account the structural breaks and asymmetric effects. The non-parametric quantile regression can be expressed as in Eq. (1):

$$Y_t = \beta^{\theta}(X_t) + \varepsilon_t^{\theta} \tag{1}$$

where Y_t is the dependent variable and X_t is the explanatory variable at time t. $\beta^{\theta}(.)$ denotes the effect of the θ quantile of the explanatory variable and ε_t^{θ} is the error term that has a zero θ^{th} quantile [59]. By taking the first-order Taylor expansion for β^{θ} around X_t, it can be defined as in Eq. (2):

$$\beta^{\theta}(X_t) \approx \beta^{\theta} X^{\tau} + \beta^{\theta'}(X^{\tau})(X_t - X^{\tau}) \tag{2}$$

$\beta^{\theta'}$ refers to the partial derivative of $\beta^{\theta}(X_t)$. Finally, the QQ method can be rewritten as in Eq. (3):

$$Y_t = \beta_0(\theta,\tau) + \beta_1(\theta,\tau)(X_t - X^{\tau}) + \varepsilon_t^{\theta} \tag{3}$$

The choice of bandwidth is particularly important when doing a nonparametric analysis because it influences the speed of the results and simplifies the objective point [60].

3.3.2. QR model

To estimate conditional quantile functions, the QR model [58] is based on the minimization of weighted absolute deviations. The QR model is given in Eq. (4):

$$Q_Y(\tau) = F_Y^{-1}(\tau) \tag{4}$$

where $F_Y(y)$ is the probability density function $(Prob(Y) \leq y)$. The τ-quantile regression, $0 < \tau < 1$, can be defined by solving the following minimization problem [61]:

$$Q(\widehat{\beta}_\tau) = \sum_{y_{ij} > \widehat{\beta}_\tau X_{ij}} \tau \left| y_{ij} - \widehat{\beta}_\tau X_{ij} \right| + \sum_{y_{ij} < \widehat{\beta}_\tau X_{ij}} (1-\tau) \left| y_{ij} - \widehat{\beta}_\tau X_{ij} \right| \tag{5}$$

in Eq. (5), the QR approach allows for understanding variables outside the data's mean.

Also, the GQ method is a kernel-based nonparametric approach to examine causal relationships across all quantiles of the distribution. Thus, this method offers information on the conditional distribution's tails. It allows for nonlinear dependence and is less sensitive to the nonnormality of data [57]. The null hypothesis of τ-quantile Granger non-causality from X_t to Y_t is defined as follows:

$$H_0 : Q_{\tau}^{Y,X}\left(Y_t I_t^{Y}\right) \quad 0 < \tau < 1 \tag{6}$$

where $(I_t^Y, I_t^X) \in R^d$ is the explanatory vector. When the conditional quantile $Q_{\tau}^{Y,X}(Y_t I_t^Y)$ is completely specified by a parametric quantile model $m(I_t^Y, \theta_0(\tau))$ where 1 [.] is an indicator function, the null hypothesis can be rewritten [51] as in Eq. (7):

$$E\left\{1\left[Y_t - m\left(I_t^Y, \theta_0(\tau)\right)\right] - \tau I_t^Y, I_t^X\right\} = 0 \quad 0 < \tau < 1 \tag{7}$$

4. Empirical results

4.1. Fundemantal statistics

Table 2 presents descriptive statistics of the variables.

Table 2
Descriptive statistics of variables.

Country	Variable	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis	JB	JB Prob.
DEU	CO_2	0.39	0.40	1.09	0.07	0.24	0.20	1.95	80.11	0.0000
	COAL	411.73	417.88	785.79	130.54	145.34	0.06	2.22	39.16	0.0000
	GAS	151.04	147.77	301.43	43.86	60.09	0.35	2.29	63.75	0.0000
	OIL	7.93	9.46	15.93	0.19	4.13	−0.86	2.61	196.70	0.0000
	HYDRO	87.05	87.53	113.71	53.70	9.62	−0.13	2.69	10.39	0.0055
	SOLAR	126.96	121.18	333.50	5.34	83.97	0.28	1.91	95.85	0.0000
	WIND	332.84	281.19	821.85	27.34	214.07	0.68	2.37	143.43	0.0000
ESP	CO_2	0.10	0.10	0.21	0.06	0.04	0.47	1.99	120.63	0.0000
	COAL	19.13	14.90	101.10	0.00	14.88	2.86	13.63	9270.44	0.0000
	GAS	187.71	177.11	381.82	55.34	71.78	0.52	2.50	85.95	0.0000
	OIL	4.32	4.24	7.67	0.90	1.62	0.00	2.07	54.66	0.0000
	HYDRO	86.31	77.32	213.19	25.61	36.11	1.03	3.63	297.52	0.0000
	SOLAR	62.57	56.98	154.84	4.43	33.82	0.53	2.45	90.40	0.0000
	WIND	155.11	138.15	399.34	19.02	82.43	0.80	3.00	164.30	0.0000
FRA	CO_2	0.22	0.22	0.50	0.08	0.11	0.31	1.90	101.19	0.0000
	COAL	6.96	0.83	46.18	0.00	10.86	1.76	5.19	1090.72	0.0000
	GAS	103.10	96.34	216.99	10.68	54.43	0.22	2.11	63.35	0.0000
	OIL	4.19	4.01	7.18	1.31	0.90	0.67	2.68	120.42	0.0000
	HYDRO	185.29	183.19	325.63	88.26	49.24	0.30	2.46	41.10	0.0000
	SOLAR	37.97	36.04	93.81	6.21	19.45	0.51	2.65	74.37	0.0000
	WIND	92.89	79.24	200.00	17.42	51.83	0.56	2.07	135.77	0.0000
ITA	CO_2	0.21	0.20	0.51	0.08	0.12	0.34	1.72	133.46	0.0000
	COAL	59.73	57.30	113.74	21.31	18.23	0.40	2.54	55.14	0.0000
	GAS	311.64	318.65	573.06	92.29	94.83	0.01	2.25	36.00	0.0000
	OIL	4.32	3.31	13.01	0.27	3.44	0.84	2.59	191.54	0.0000
	HYDRO	114.36	108.49	217.83	38.65	38.68	0.40	2.41	62.70	0.0000
	SOLAR	55.49	56.89	106.23	0.00	24.54	−0.12	1.86	86.48	0.0000
	WIND	54.92	47.16	156.50	4.20	35.41	0.74	2.71	145.48	0.0000

Std. Dev. and JB denote the standard deviation and Jarque-Bera, in order.

DEU has relatively higher mean CO_2 emissions (0.39) than ESP (0.10), FRA (0.22), and ITA (0.21). The fact that ESP has the lowest CO_2 emissions can be explained by its GDP level. As of 2023, DEU has a GDP of 17,700,899 million USD, France 3,049,016 million USD, Italy 2,186,082 million USD and ESP 1,582,054 million USD [62]. Theoretically, with the scale effect, high GDP levels of countries can lead to increased production and high CO_2. Therefore, it is reasonable that Spain has minimum CO_2 with lowest GDP compared to other EU countries.

In addition, DEU has substantially higher mean values for COAL (411.73), OIL (7.93), SOLAR (126.96), and WIND (332.84) compared to the other countries. Conversely, Spain has lower mean CO_2 emissions (0.10) and relatively higher mean values for GAS (187.71) among all countries. France has lower values for all variables, with notable mean

Table 3
Pairwise correlation matrix of variables.

Country	Variable	CO_2	COAL	GAS	OIL	HYDRO	SOLAR	WIND
DEU	CO_2	1.00						
	COAL	0.16	1.00					
	GAS	0.13	0.80	1.00				
	OIL	−0.01	0.02	0.07	1.00			
	HYDRO	−0.02	−0.17	−0.11	0.08	1.00		
	SOLAR	−0.05	0.00	−0.02	0.04	0.00	1.00	
	WIND	−0.08	−0.48	−0.46	0.02	0.18	−0.11	1.00
ESP	CO_2	1.00						
	COAL	0.03	1.00					
	GAS	0.06	0.39	1.00				
	OIL	0.00	0.41	0.60	1.00			
	HYDRO	0.08	0.29	0.48	0.47	1.00		
	SOLAR	0.03	0.00	0.02	−0.03	−0.06	1.00	
	WIND	−0.03	−0.23	−0.59	−0.15	−0.41	−0.19	1.00
FRA	CO_2	1.00						
	COAL	0.04	1.00					
	GAS	0.15	0.18	1.00				
	OIL	0.02	0.04	0.09	1.00			
	HYDRO	0.14	0.25	0.33	0.13	1.00		
	SOLAR	0.12	0.05	0.06	−0.01	0.01	1.00	
	WIND	−0.13	−0.04	−0.29	−0.08	−0.17	−0.21	1.00
ITA	CO_2	1.00						
	COAL	0.00	1.00					
	GAS	0.01	0.25	1.00				
	OIL	0.05	0.08	0.25	1.00			
	HYDRO	0.03	0.19	0.60	0.17	1.00		
	SOLAR	0.03	−0.06	−0.04	−0.01	−0.07	1.00	
	WIND	0.01	−0.19	−0.23	−0.12	−0.03	−0.10	1.00

Values denote correlation coefficients between variables.

values for COAL (6.96) and GAS (103.10), but relatively higher mean values for HYDRO (185.29). Italy has a lower mean for WIND (54.92), but a higher mean for GAS (311.64) and HYDRO (114.36).

Positive skewness values are observed for all variables for each country, except for OIL and HYDRO in DEU, and SOLAR in ITA. These skewness values indicate an asymmetry (right-skewed) in the distributions of these variables. Higher kurtosis values indicate more outliers or extreme values in the distribution. In Table 2, significantly higher kurtosis values are observed for HYDRO in DEU, COAL, HYDRO, and WIND in ESP, COAL, OIL, and SOLAR in FRA, and WIND in ITA. These variables have distributions that are more peaked and have wider tails compared to a normal distribution. A higher CV indicates higher relative variability or dispersion in the data. In addition, almost all variables for each country have significant variability. In addition, the JB test does not fulfill the normality assumption for all variables in each country. Table 3 shows the correlations between the variables used in the study for each country.

In DEU, there is a weak correlation between CO_2 emissions versus other variables. However, there is a strong positive correlation between COAL and GAS (0.80). On the other hand, WIND shows a relatively strong negative correlation with COAL (−0.48) and GAS (−0.46). In ESP, there are generally weak to moderate positive correlations between CO_2 emissions and energy sources. In particular, there are moderate positive correlations between OIL and GAS (0.60), HYDRO and GAS (0.48), and HYDRO and OIL (0.47). WIND shows weak negative correlations with several variables, including GAS (−0.59) and HYDRO (−0.41). In FRA, CO_2 emissions show weak correlations with other energy sources. HYDRO exhibits a moderate positive correlation with COAL (0.25) and GAS (0.33), while WIND and GAS have a moderate negative correlation (−0.29). For ITA, the correlations among variables are generally weak. In particular, there is a strong positive correlation between HYDRO and GAS (0.60).

Table 4 provides a comprehensive overview of the results of the nonlinearity tests performed. This offers valuable insights into the nature of the relationships between the variables and the presence of nonlinearity across different dimensions.

The results of the BDS nonlinearity test with p-values indicating the extent of nonlinearity for different variables and dimensions in the different countries show that the p-values for each variable and dimension are consistently low (0.0000) in all countries. This confirms a strong indication of nonlinearity. In other words, the BDS test suggests that the relationship between the variables is not linear. Accordingly, the usage of nonlinear methods (e.g., QQ, GQ, QR) is much more appropriate than the use of linear approaches.

4.2. QQ results

Fig. 2 presents the quantile-based effects of various energy sources on residential CO_2 emissions. Fig. 2 illustrates the effect of COAL on residential CO_2 emissions.

As shown in Fig. 2, although there is a complex relationship between COAL and CO_2, there are two areas, where the effect of COAL on CO_2 is statistically significant in DEU, ESP, and ITA. Within the quantile-based analysis, COAL is shown to have a notably increasing effect on CO_2 within specific quantile ranges for different countries. In the case of DEU, quantiles above 0.70 show a significant positive relationship for both COAL and CO_2. Similarly, for ESP, quantiles for COAL exceeding 0.70 coincide with CO_2 quantiles ranging from 0.55 to 0.80. Conversely, ITA exhibits lower quantiles below 0.25 for COAL, while CO_2 quantiles above 0.80 are observed. In contrast to DEU, ESP, and ITA, the relationship between COAL and CO_2 emissions demonstrates a different pattern for FRA. Across various quantile combinations, the effect of COAL on CO_2 emissions tends toward 0, except in the region, where CO_2 quantiles fall below 0.10. Fig. 3 shows the effect of GAS on residential CO_2 emissions.

In the region characterized by the upper quartiles of both GAS and CO_2, the relationship between GAS and CO_2 in DEU shows a comparatively higher efficiency. In the other regions, however, this relationship is relatively weak, with an effect between 0 and 0.5. In ESP, too, there is only one area in which the effect of GAS on CO_2 is significantly higher.

Table 4
Nonlinearity results.

Country	Variable	Dimensions					Results
		2	3	4	5	6	
DEU	CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	COAL	0.0505	0.0000	0.0000	0.0000	0.0000	NL
	GAS	0.0056	0.0872	0.0514	0.0430	0.0006	NL
	OIL	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	HYDRO	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	SOLAR	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	WIND	0.0011	0.0000	0.0000	0.0000	0.0000	NL
ESP	CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	COAL	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	GAS	0.6676	0.0050	0.0000	0.0000	0.0000	NL
	OIL	0.0076	0.0000	0.0000	0.0000	0.0000	NL
	HYDRO	0.0181	0.0000	0.0000	0.0000	0.0000	NL
	SOLAR	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	WIND	0.0001	0.0000	0.0000	0.0000	0.0000	NL
FRA	CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	COAL	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	GAS	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	OIL	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	HYDRO	0.0022	0.0000	0.0000	0.0000	0.0000	NL
	SOLAR	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	WIND	0.0556	0.0002	0.0000	0.0000	0.0000	NL
ITA	CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	COAL	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	GAS	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	OIL	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	HYDRO	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	SOLAR	0.0000	0.0000	0.0000	0.0000	0.0000	NL
	WIND	0.0000	0.0000	0.0000	0.0000	0.0000	NL

Values indicate p-values. NL denotes nonlinearity.

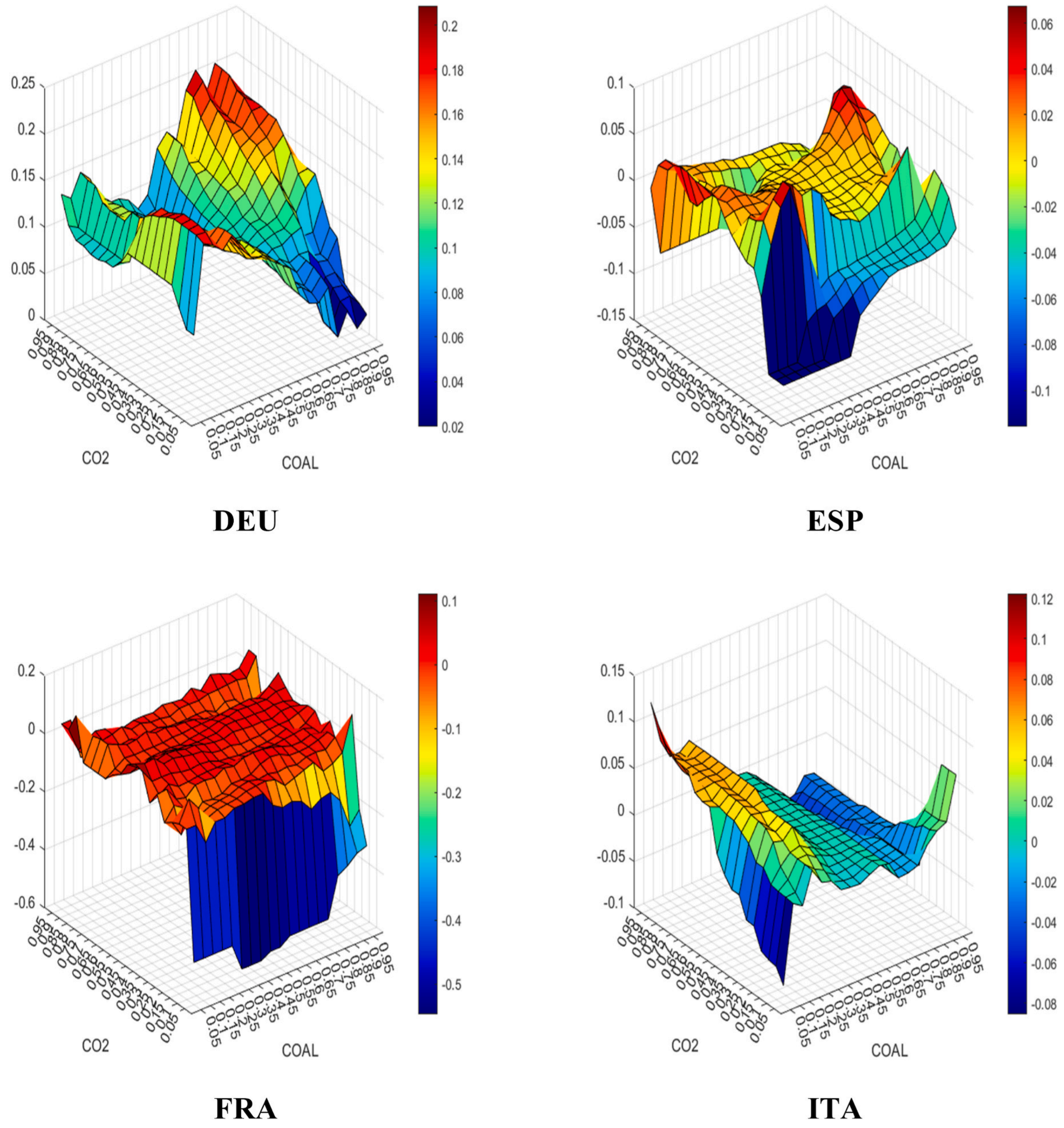


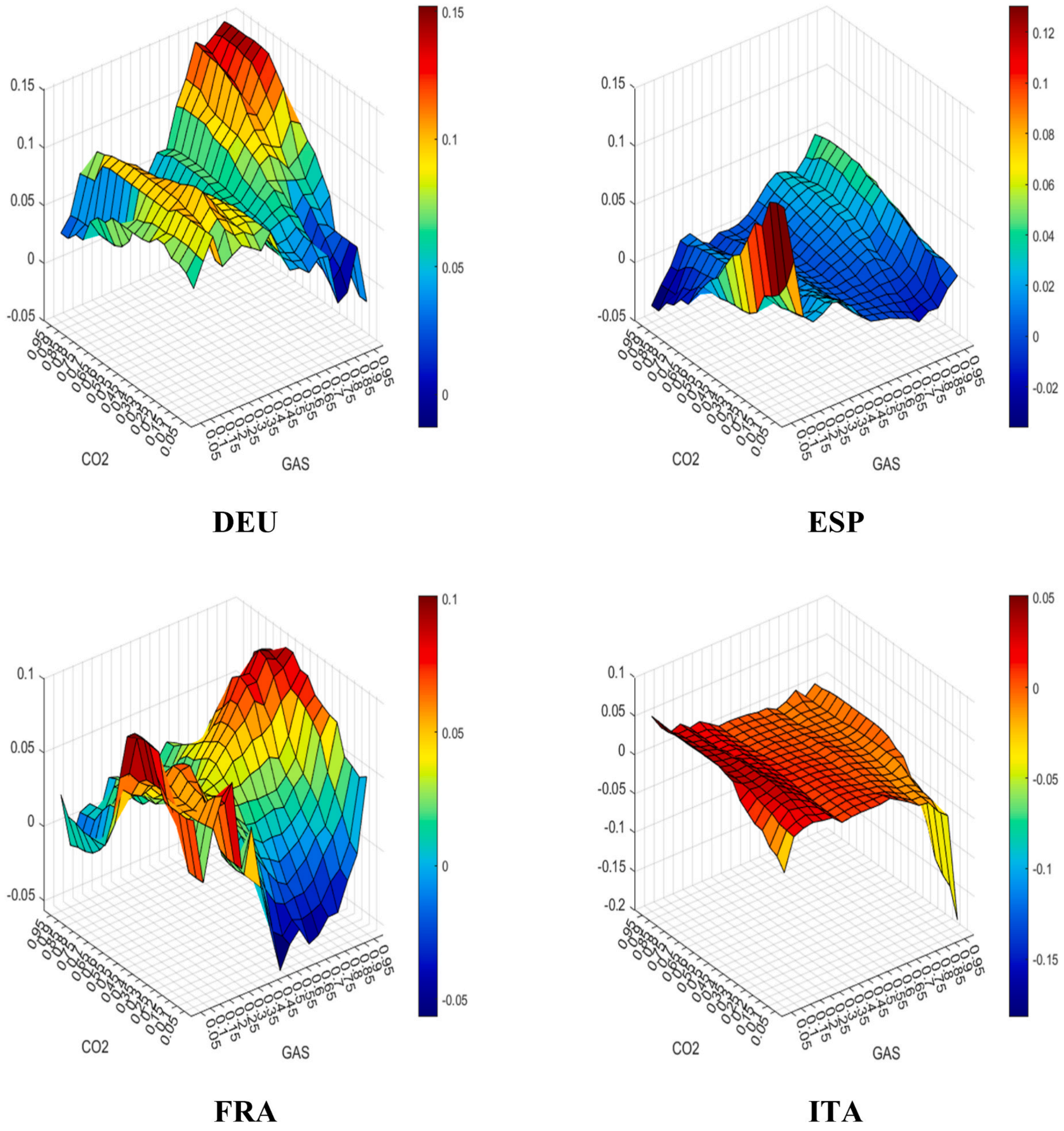
Fig. 2. Coal effect on residential CO_2 emissions.

This range consists of quantiles that are smaller than 0.5 for both GAS and CO_2. In analyzing the effect of GAS on CO_2 in FRA, it becomes clear that this relationship has a distinct pattern that resembles a "saddle" once examined in terms of quantiles. This pattern suggests that the effect is comparatively more pronounced within the GAS quantiles below 0.40 or above 0.70 and within the intermediate CO_2 quantiles. For ITA, this effect is zero in all quantile combinations, except for the highest quantiles of GAS and the lowest quantiles of CO_2. Fig. 4 illustrates the quantile-based effect of OIL on residential CO_2 emissions.

In ITA and DEU, the effect of OIL on CO_2 remains zero near the median of the quantiles for both variables. However, the effect strengthens in the regions along the diagonal. In contrast, ESP shows an initial decrease in the positive effect as CO_2 emissions move from higher quantiles to lower quantiles. Subsequently, this effect reverses, becomes negative, and gains strength. In FRA, the relationship between OIL and CO_2 emissions exhibits a "V-shaped" pattern. This suggests that the effect of OIL on CO_2 emissions is substantial for both the lower and upper quantiles of OIL, while the effect around the median quantile is relatively small. Fig. 5 illustrates the quantile-based effect of HYDRO on residential CO_2 emissions.

In DEU, ESP, and ITA, the effect of HYDRO on CO_2 emissions exhibits an ascending trend as the quantiles of HYDRO increase. It is noteworthy that this effect remains consistent across the different CO_2 quantiles. This suggests that this effect is primarily due to the distribution of the quantiles within the HYDRO variable. In FRA, the association between HYDRO and CO_2 emissions displays a pronounced "V-shaped" pattern. From this, it can be deduced that the influence of HYDRO on CO_2 emissions is significant for both the lower and upper quantiles of HYDRO, while the effect around the median quantile is comparatively smaller. Fig. 6 demonstrates the effect of SOLAR on residential CO_2 emissions.

In DEU, the effect of SOLAR on CO_2 emissions is relatively higher in regions, where the CO_2 quantiles are above 0.70 or below 0.40. In particular, the effect of SOLAR on CO_2 exhibits a positive and significant relationship in both the upper quartiles (Q75) and the lower quartiles (Q25) of SOLAR and CO_2 in ESP, FRA, and ITA. However, in cases where



DEU

ESP

FRA

ITA

Fig. 3. Gas effect on residential CO_2 emissions.

the SOLAR quantiles are above 0.80 and the CO_2 quantiles are below 0.30, this influence becomes negative. Fig. 7 shows the effect of WIND on residential CO_2 emissions.

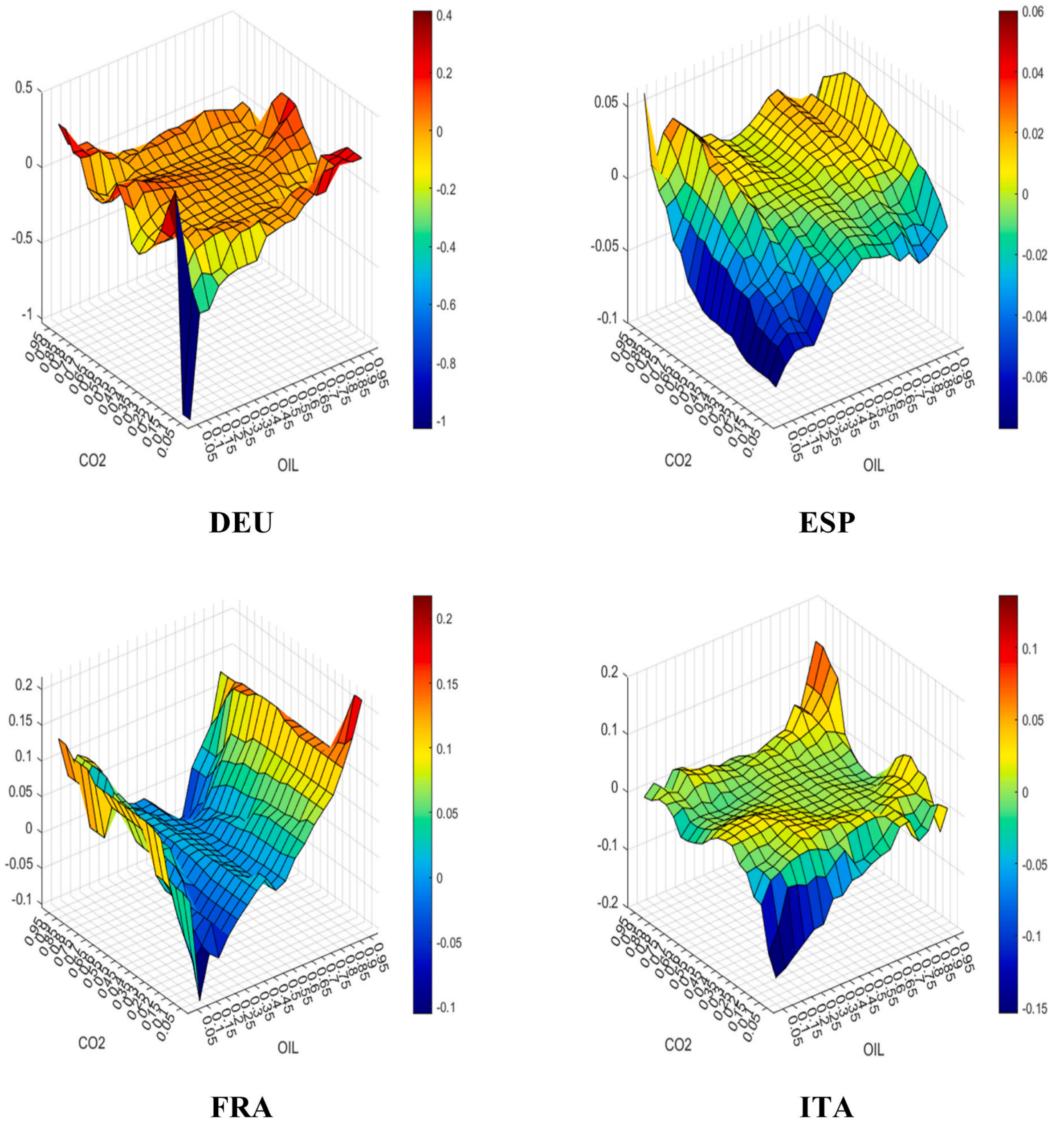
The association between WIND and CO_2 is more complicated compared to other factors. In DEU, ESP, and ITA in particular, the effect of WIND on CO_2 emissions remains zero near the median quantiles for both variables. Nevertheless, this effect becomes stronger in the regions along the diagonal, indicating a heightened relationship between WIND and CO_2 in these areas. In contrast, for ITA, the effect of WIND on CO_2 is relatively high in the areas with higher quantiles of CO_2. From the higher to the lower quantiles of CO_2, this effect becomes weaker.

4.3. GQ results

Table 5 summarizes the GQ results conducted to investigate the causal relationships between the variables. It provides information on the direction of causality and the corresponding tau values (e.g., 0.05 to 0.95) at different levels of significance.

In the case of DEU, the p-values for the causal pathways COAL→ CO_2, GAS→ CO_2, OIL→ CO_2, HYDRO→ CO_2, SOLAR→ CO_2, and WIND→ CO_2 consistently exhibit a value of 0.00 across all tested significance levels, except for the quantiles 0.05, 0.50, and 0.95. This observation provides substantial empirical support for the refutation of the null hypothesis that there is no Granger causality between the first and second variables. Thus, these findings offer robust evidence for a statistically significant causal relationship between the variables.

For ESP and FRA, the p-values for almost all tested causal pathways (COAL→ CO_2, GAS→ CO_2, OIL→ CO_2, HYDRO→ CO_2, SOLAR→ CO_2, and WIND→ CO_2) are consistently below the significance level of 0.05 for all tested quantiles, except for the quantiles 0.05, 0.50, and 0.95. This observation indicates solid statistical support for the existence of a significant causal relationship among the variables under investigation. It is important to emphasize that the p-values signify the likelihood of obtaining the observed test results assuming the absence of a causal relationship. Thus, the remarkably low p-values provide strong empirical evidence for the alternative hypothesis, substantiating the presence



DEU

ESP

FRA

ITA

Fig. 4. Oil effect on residential CO_2 emissions.

of a causality between the variables.

In contrast to the findings in DEU, ESP, and FRA, the analysis of ITA reveals that the p-values for almost all causal paths examined are consistently below the significance level of 0.05 across all quantiles tested, except the 0.05, 0.50, 0.90, and 0.95 quantiles.

4.4. *Robustness check*

To validate the robustness of the QQ results, the study performs the QR methods, and the results are presented in Annexes 1-6 in detail. Also, Table 6 presents a summary of the robustness check focusing on the correlation between QQ and QR methods.

In DEU, a comprehensive analysis reveals a significant correlation between several variables and CO_2. In particular, the variables HYDRO, SOLAR, COAL, and GAS show a strong correlation with CO_2, exceeding 80%. These findings indicate a robust relationship between these variables and CO_2 emissions in DEU. On the other hand, the variables WIND and OIL demonstrate a moderate correlation with CO_2. The percentage of correlation for WIND and OIL is not as high as for the variables mentioned above but still indicates a recognizable relationship.

For ESP, FRA, and ITA, a thorough analysis reveals noteworthy bivariate correlations between the variables examined. The correlations between the individual variables and CO_2 are consistently significant and, with a few exceptions, exceed the 80% threshold. In ESP, the correlations between CO_2 and COAL, SOLAR, and WIND are below the high threshold of 80%. The correlation between CO_2 and COAL is also an exception in FRA. Finally, at ITA, the correlation between CO_2 and OIL does not reach the high threshold observed for the other variables.

Overall, these findings underscore the existence of strong associations between most variables and residential CO_2 emissions. Thus, the robustness check contributes to a comprehensive understanding of the bivariate correlations between variables and CO_2 emissions.

4.5. *Summarized results*

Table 7 provides a comprehensive overview of the effect of the EG

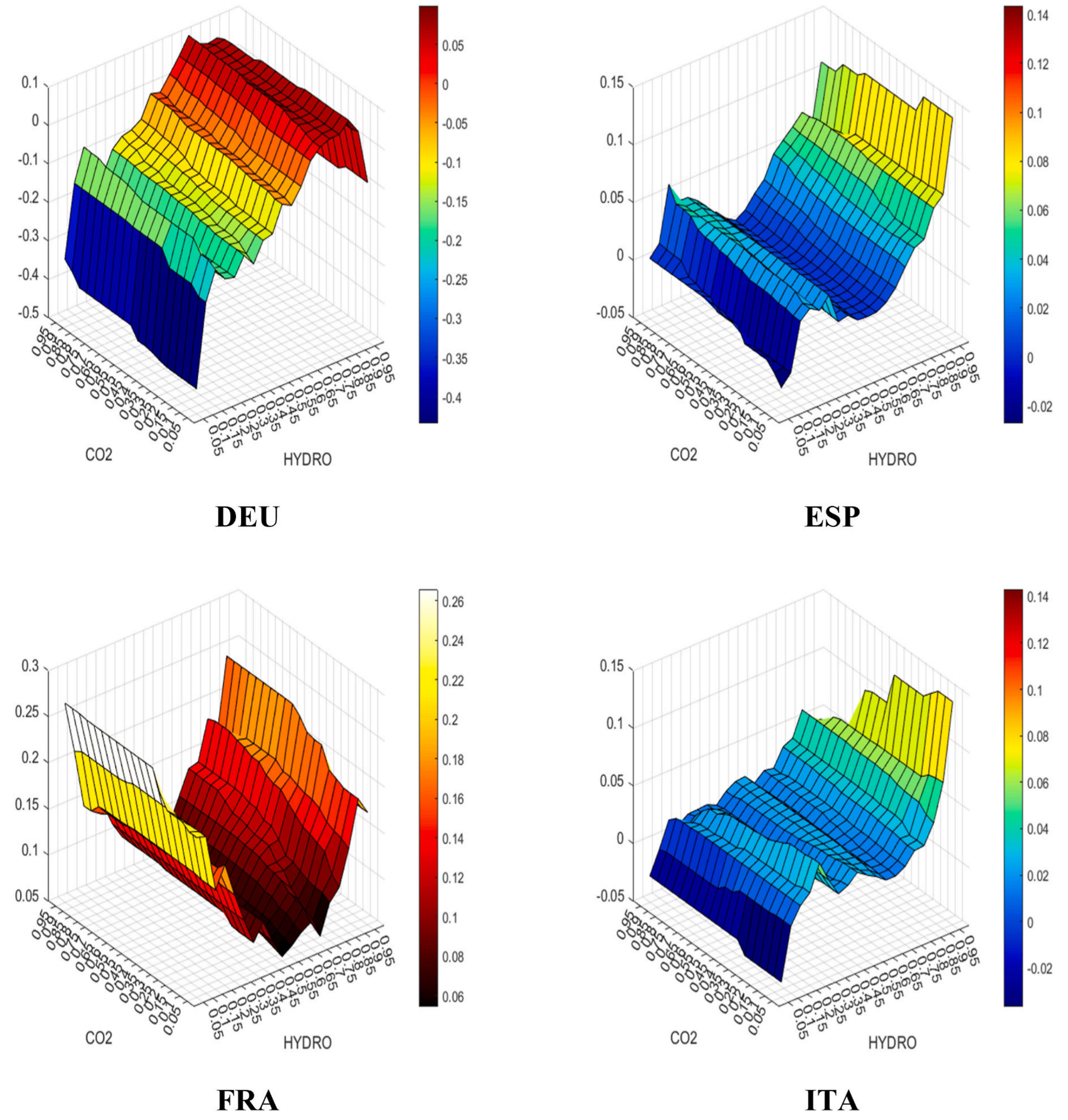


Fig. 5. Hydro effect on residential CO_2 emissions.

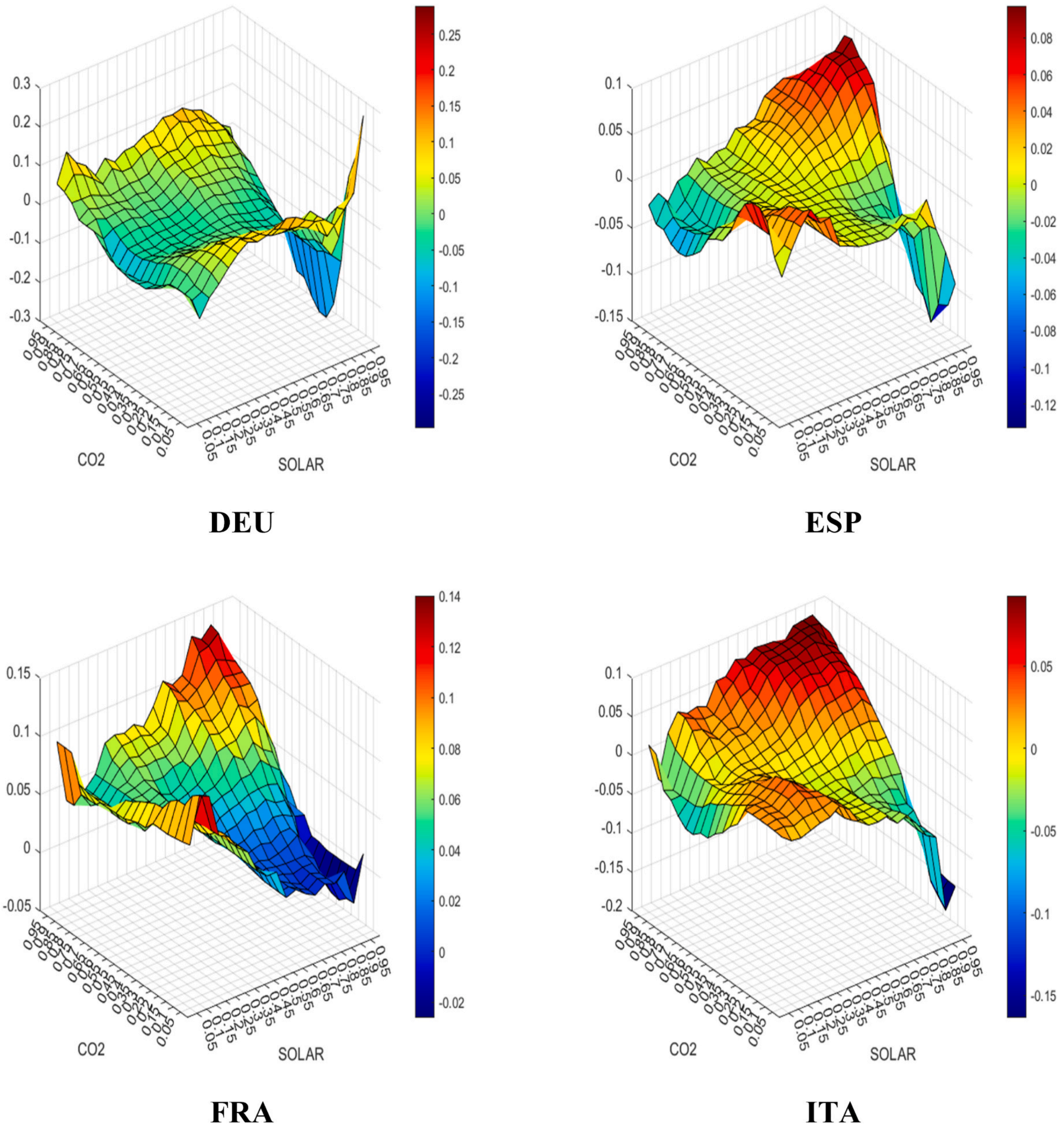
indicators on residential CO_2 emissions in different quantiles. The quantiles of CO_2 and EG represent different levels of CO_2 emissions and different levels of EG, respectively.

In DEU, the effects vary depending on the quantiles. At the lower quantiles, COAL, GAS, and SOLAR have an increasing effect on CO_2 emissions, while OIL, HYDRO, and WIND have a decreasing effect. At the middle quantiles, COAL and GAS continue to increase CO_2 emissions, while OIL, HYDRO, and WIND have mixed effects. At higher quantiles, all variables except SOLAR have an increasing effect on CO_2 emissions.In ESP, COAL, OIL, HYDRO, and SOLAR have a decreasing effect at the lower quantiles, while GAS and WIND have an increasing effect on CO_2 emissions. At middle and higher quantiles, COAL, OIL, HYDRO, and SOLAR have an increasing effect, while GAS has mixed effects. At higher quantiles, all variables except WIND have an increasing effect on CO_2 emissions.

In FRA, GAS, HYDRO, and SOLAR have an increasing effect on CO_2 emissions at all quantiles, whereas COAL and OIL have a decreasing effect at lower quantiles and an increasing effect at middle and higher quantiles. At middle quantiles, all variables except WIND have an increasing effect. At higher quantiles, all variables except COAL and WIND have an increasing effect on CO_2 emissions.

In ITA, at lower quantiles, all factors except SOLAR have a decreasing effect on CO_2 emissions, while WIND has a decreasing effect. At middle quantiles, all factors except GAS have an increasing effect on CO_2 emissions. At higher quantiles, COAL and SOLAR have a decreasing effect, while GAS, OIL, HYDRO, and WIND have an increasing effect on CO_2 emissions.

Despite renewable energy sources are eco-friendly, several studies indicate that these resources are insufficient for CO_2 and ecological footprint reduction [63,64]. In fact, Boluk and Mert [65] stated that renewable energies increase GHG emissions in EU countries. In this context, it is possible that renewable energy types are positively correlated with CO_2 in Italy, Spain and France, but negatively correlated in Germany. The reason for this situation is that other EU countries do not have as developed technologies in the field of renewable energy as Germany. Renewable energy R&D expenditures in Germany are 276



DEU

ESP

FRA

ITA

Fig. 6. Solar effect on residential CO_2 emissions.

million USD in 2020, while Italy's are 108 million USD and Spain's are 52 million USD [66]. In addition, Germany's renewable energy consumption in 2022 (2.45 EJ) is higher than the consumption of Italy (0.76 EJ), France (0.81 EJ) and Spain (1.04 EJ). Insufficient renewable consumption and R&D investments in other EU countries compared to Germany are the main reasons for the difference in findings.

5. Conclusion, policy implications, and future research

5.1. Discussion and conclusion

The world has been confronted with serious environmental problems in recent decades. Current literature indicates that high energy consumption is one of the main causes of these problems. Accordingly, many studies have examined the relationship between the environment and energy consumption. Some of these recent studies focus on analyzing data at a disaggregated level rather than at an aggregated level to gain deeper insights into the dynamic link between the environment and energy consumption. The EU has recently been facing an energy crisis that is affecting the energy market and forcing EU countries to make a choice between alternative energy sources to be used in the EG. In this context, the study comprehensively analyzes the impact of EG from different fossil fuels (coal, gas, oil) and renewable energy sources (hydro, solar, wind) on residential CO_2 emissions by considering that the behavior of the residential sector as the last consumer is of great importance for the environment.

The EU-4 countries are examined by incorporating the latest high-frequency data (daily) from January 2, 2019, to March 10, 2023, and applying novel non-linear quantile-based econometric approaches. To the best of the researcher's knowledge, no study has examined the impact of the EG at a disaggregated level on residential CO_2 emissions for the EU-4 countries using daily data and applying novel non-linear quantile-based econometric models. Therefore, the study attempts to provide answers to the question of which EU country can effectively reduce residential CO_2 emissions by using which EG sources.

The comprehensive econometric approach applied in the study

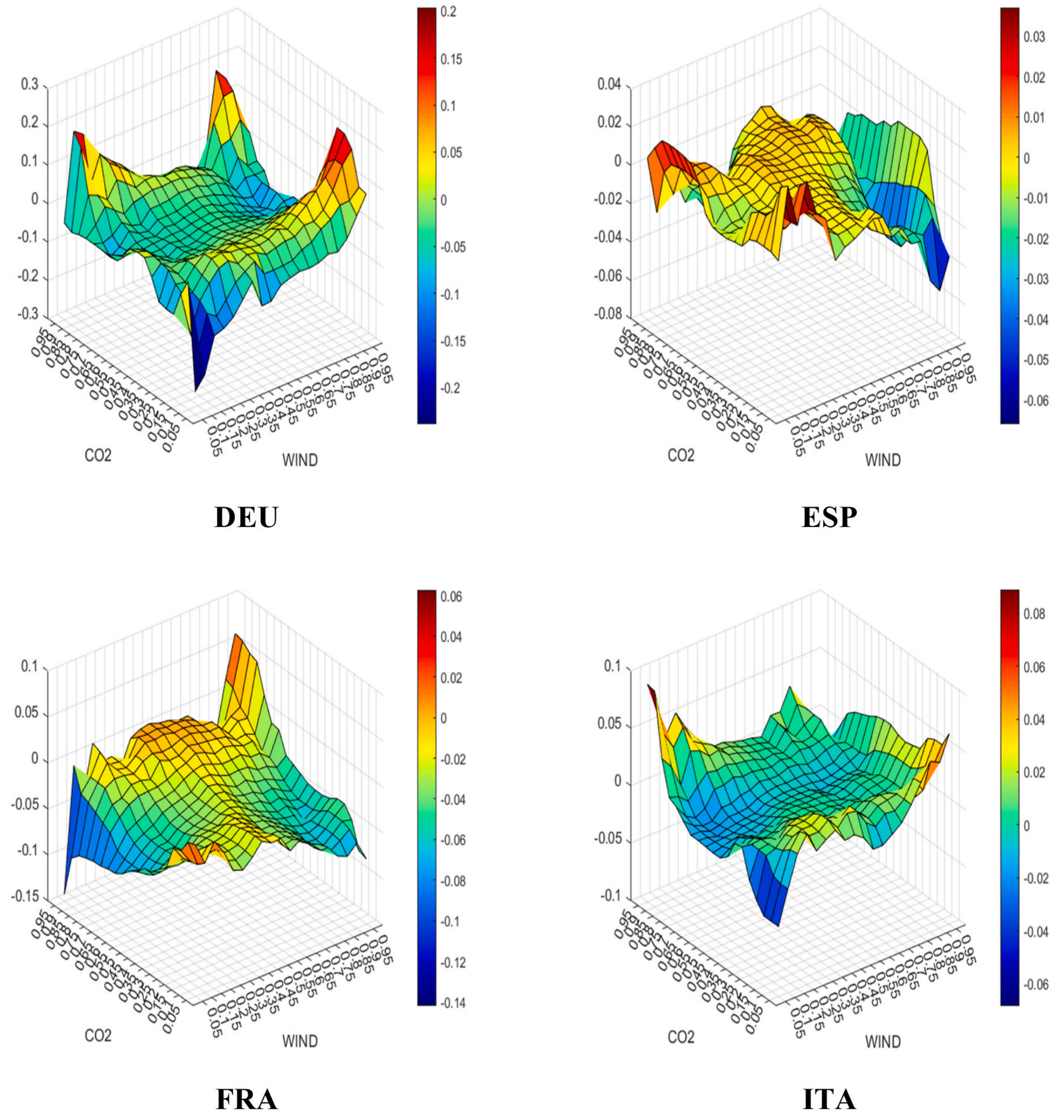


Fig. 7. Wind effect on residential CO_2 emissions.

presents that EG from fossil fuels (coal, natural gas, and oil) generally has a stimulating effect in all EU-4 countries at higher quantiles. EG from hydro has an increasing effect at higher quantiles, while it has a decreasing effect at lower and middle quantiles in all EU-4 countries except France; EG from solar energy has a decreasing effect at higher quantiles in all countries except Spain and France; EG from wind power has a decreasing effect at higher quantiles in Spain and France; all subtypes of disaggregated level fossil and renewable EG have a causal effect on residential CO_2 emissions except for some quantiles; the findings gathered are consistent based on the alternative empirical method. In summary, the effect size and causal effect of sources of EG (i.e., subtypes of fossil and renewable) on residential CO_2 emissions vary by source, quantile, and country.

The results collected in this study answer the research question of which EU country can effectively reduce residential CO_2 emissions by using which EG sources. In this context, the study concludes that of all the alternatives considered in the study, Germany and Italy should focus on solar EG, while wind EG is much more suitable for Spain and France to slow down CO_2 emissions from the residential sector. Thus, the study provides clear answers to the research question it is looking for.

The results defined in the study are generally consistent with current literature, e.g., Kartal et al. [44] for EG from fossil fuels (COAL, GAS, OIL) and Ozcan et al. [67] for EG from renewable sources (HYDRO, SOLAR, WIND). In line with these studies, the study concludes that renewable EG is the best option to mitigate climate change and that the best alternative is different for each EU-4 country. This study differs from these studies in that it defines the best renewable EG alternative for each EU-4 country, adding depth to the current literature. While the results are consistent with both prior expectations and theoretical background, the results extend knowledge by specifying the best EG alternative for each EU-4 country. This allows each EU-4 country to make a better decision on which EG should be prioritized to meet the countries' carbon neutrality targets, taking into account EG capacity, and addressing the current energy crisis.

Table 5
GQ results.

Country	Causality	Quantile																		
		0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95
DEU	COAL⇒CO_2	0.30	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27
	GAS⇒CO_2	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.24
	OIL⇒CO_2	0.32	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21
	HYDRO⇒CO_2	0.26	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26
	SOLAR⇒CO_2	0.25	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15
	WIND⇒CO_2	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
ESP	COAL⇒CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	GAS⇒CO_2	0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00
	OIL⇒CO_2	0.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00
	HYDRO⇒CO_2	0.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00
	SOLAR⇒CO_2	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.03
	WIND⇒CO_2	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FRA	COAL⇒CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	GAS⇒CO_2	0.82	0.00	0.01	0.00	0.02	0.01	0.00	0.04	0.01	0.40	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.64
	OIL⇒CO_2	0.71	0.00	0.00	0.00	0.01	0.00	0.00	0.04	0.01	0.44	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.69
	HYDRO⇒CO_2	0.75	0.00	0.00	0.00	0.01	0.00	0.00	0.04	0.01	0.51	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.74
	SOLAR⇒CO_2	0.63	0.00	0.01	0.00	0.01	0.00	0.00	0.03	0.01	0.26	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11
	WIND⇒CO_2	0.43	0.00	0.01	0.00	0.01	0.00	0.00	0.03	0.00	0.09	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
ITA	COAL⇒CO_2	0.06	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.55
	GAS⇒CO_2	0.05	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.64
	OIL⇒CO_2	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.55
	HYDRO⇒CO_2	0.06	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.02	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.65
	SOLAR⇒CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	WIND⇒CO_2	0.04	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00

Values represent p-values.

Table 6
Comparison of QQ and QR methods.

Country	Variable	Correlation (%)	Country	Variable	Correlation (%)
DEU	COAL & CO_2	93.12	FRA	COAL & CO_2	59.97
	GAS & CO_2	84.51		GAS & CO_2	90.91
	OIL & CO_2	30.36		OIL & CO_2	97.82
	HYDRO & CO_2	99.75		HYDRO & CO_2	99.21
	SOLAR & CO_2	96.18		SOLAR & CO_2	96.89
	WIND & CO_2	44.55		WIND & CO_2	88.39
ESP	COAL & CO_2	68.20	ITA	COAL & CO_2	95.99
	GAS & CO_2	91.82		GAS & CO_2	98.98
	OIL & CO_2	95.53		OIL & CO_2	70.46
	HYDRO & CO_2	99.79		HYDRO & CO_2	99.73
	SOLAR & CO_2	63.76		SOLAR & CO_2	79.47
	WIND & CO_2	76.82		WIND & CO_2	85.62

5.2. *Policy implications*

The study defines that fossil EG in the EU-4 countries generally has an increasing effect on residential CO_2 emissions, although, for some lower quantiles, there is a decreasing effect. Of course, there are some exceptions. For example, oil EG has a reducing effect on residential CO_2 emissions in the lower quantiles in all countries. The main reason for this is that oil accounts for almost 1% of total EG. Therefore, the effect of oil EG on residential CO_2 emissions is quite limited. Similarly, the impact of coal EG on the lower quantiles in Spain, France, and Italy is less than 10% of total EG. As a relatively low-carbon energy source, EG from natural gas also has a dampening effect on the middle quantiles in Spain and on the lower and middle quantiles in Italy. All these findings on fossil EG provide an important basis for policy recommendations. Accordingly, EU-4 countries can be recommended to favor electricity generation from oil sources instead of coal and to use natural gas sources instead of oil sources. In this way, the negative impact of fossil EG on residential CO_2 emissions can be limited and less environmental damage caused.

EG from hydro has a thoroughly degrading effect in France. In the remaining EU-4 countries, hydro EG has a dampening effect at lower quantiles, while it has a stimulating effect on residential CO_2 emissions at higher quantiles. This could be because France does not use a large amount of hydro EG because of its greater reliance on nuclear EG Ref. [44] and the share of hydro in total EG is below 20% in the other EU-4 countries. Accordingly, the EU-4 countries have not benefited from hydro EG in reducing residential CO_2 emissions. Thus, Germany can benefit from hydro, while Spain and Italy can benefit from hydro to a lesser extent and it is not a good source for France. Therefore, the EU-4 countries should use hydro to an optimal extent that takes into account their respective electricity generation mix.

EG from solar and wind energy has proven to be much more effective in reducing residential CO_2 emissions. Among the alternatives, Germany and Italy can benefit from solar EG, while Spain and France can benefit from wind EG in reducing CO_2 emissions from the residential sector. It can be deduced that these countries should continue to rely on these specific EG sources. In this way, they can keep residential CO_2 emissions under control. They should also work on increasing the efficiency of other renewable EG sources to further benefit from them. For example, EU-4 countries can re-evaluate supportive measures (e.g., investment incentives, tax exemptions, and subsidies) to increase the regressive effect of inefficient renewable EG sources. In this way, they can benefit

Table 7
Summary of EG effect on residential CO_2 emissions.

Country	Quantiles of CO_2	Quantiles of EG	COAL	GAS	OIL	HYDRO	SOLAR	WIND
DEU	Lower	Lower	↑	↑	↓	↓	↑	↓
	Middle	Middle	↑	↑	↑	↓	↓	↓
	Higher	Higher	↑	↑	↑	↑	↓	↑
ESP	Lower	Lower	↓	↑	↓	↓	↓	↑
	Middle	Middle	↑	↓	↑	↑	↑	↓
	Higher	Higher	↑	↑	↑	↑	↑	↓
FRA	Lower	Lower	↓	↑	↓	↑	↑	↑
	Middle	Middle	↑	↑	↑	↑	↑	↓
	Higher	Higher	↑	↑	↑	↑	↑	↑
ITA	Lower	Lower	↓	↓	↓	↓	↑	↓
	Middle	Middle	↑	↓	↑	↑	↑	↑
	Higher	Higher	↓	↑	↑	↑	↓	↑

↑ and ↓ denote increasing and decreasing effects, in order

from all renewable EG sources to achieve the goal of carbon neutrality and reduce CO_2 emissions in the residential sector.

EU-4 countries should take into account the fact that any type of EG from fossil fuels is more or less harmful to the environment and has a stimulating effect on residential CO_2 emissions, while different types of renewable EG sources can be beneficial. Given the recent energy crisis resulting from the Russia-Ukraine conflict and the cut in natural gas supplies by Russia, EU-4 countries should consider various aspects (e.g., energy supply sources, energy security, and energy dependence) when selecting EG sources. In this context, EU-4 countries should consider relying more on indigenous sources for EG. Although fossil fuel-based EG sources rather than natural gas may be a short-term solution to ensure the security of EG, the long-term solution is ultimately to rely on renewable EG sources. Thus, it can be suggested that Germany and Italy should generate much more solar EG, while wind EG is more suitable for Spain and France. In this way, EU-4 countries can reduce their dependence on fossil fuels, use the most suitable renewable EG sources, which are indigenous and contribute to energy security, curb residential CO_2 emissions, and help combat global environmental problems.

Finally, the size of the effect and whether or not the effect is at a causal level varies by quantile, country, and disaggregated level of EG sources. Therefore, when designing their energy-related environmental policies, EU-4 countries should take into account the changing effect of EG on residential CO_2 emissions based on quantiles, countries, and EG sources.

5.3. Limitations and future research

As a first limitation, CO_2 emissions are used as an environmental indicator to study CO_2 emissions from the residential sector due to the desire to collect the most up-to-date dataset available. However, the usage of CO_2 emissions as an environmental indicator leads to a major limitation: only air pollution is considered, while other pollution (e.g., soil, water) and biocapacity are neglected. Considering this main limitation, future research can conduct new analyses using other environmental indicators.

Second, the study uses both daily and disaggregated level data for EG. New studies can consider the use of much more disaggregated level data for the residential sector at the state, province, city, and district levels, if available. In this way, a more detailed analysis of residential CO_2 emissions can also be carried out.

Third, the study applies novel quantile-based nonlinear approaches to empirical analysis. However, the econometric universe has been constantly evolving and new econometric approaches have emerged. In this context, future studies can consider using new econometric approaches (e.g., Fourier-based approach, Wavelet-based approaches, Wavelet local multiple correlations) to deepen the literature through new econometric analysis approaches.

Fourth, since the study focuses only on CO_2 emissions from the residential sector, new studies can also analyze the interaction of the residential sector with other sectors (e.g., power, industry, transportation). In addition, future studies can also consider account factors unrelated to EG (e.g., households' preference for using EG sources, the production costs of electricity from power generation sources, and retail sales prices of individual power generation sources). The researchers therefore believe that all these constraints can be positioned as further research points in new studies. By considering these points in new studies, the current knowledge can therefore be developed much further.

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Consent for publication

The authors are willing to permit the Journal to publish the article.

CRediT authorship contribution statement

Ugur Korkut Pata: Conceptualization, Writing – original draft, Writing – review & editing. **Mustafa Tevfik Kartal:** Conceptualization, Supervision, Methodology, Software, Writing – original draft. **Andrew Adewale Alola:** Writing – original draft. **Serpil Kılıç Depren:** Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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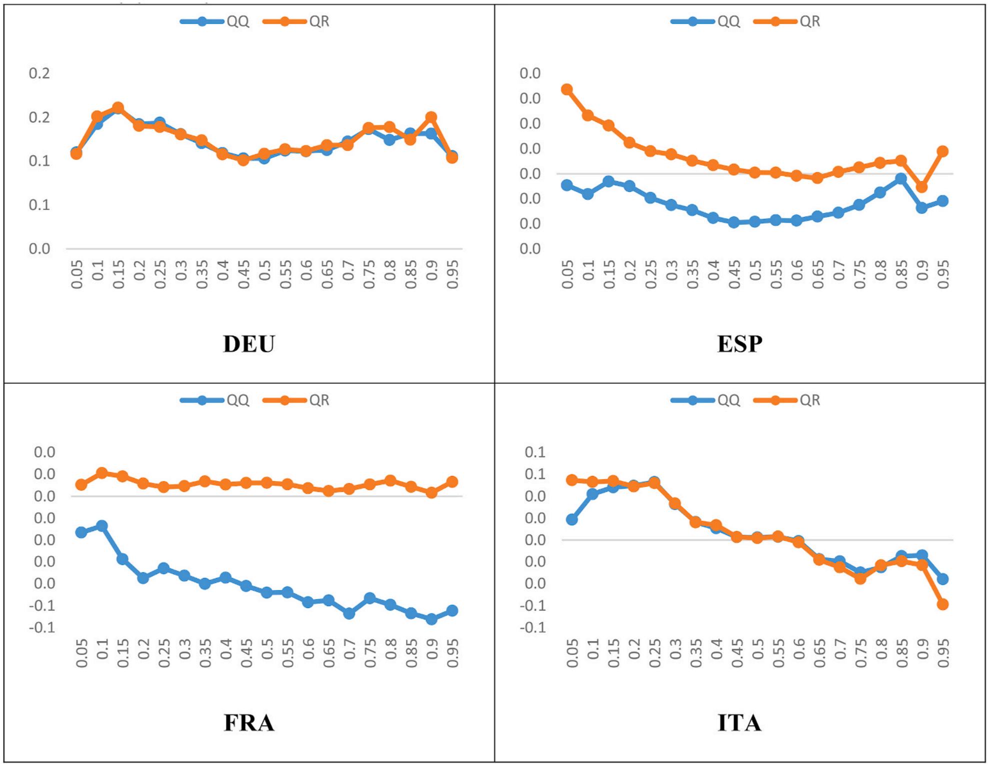
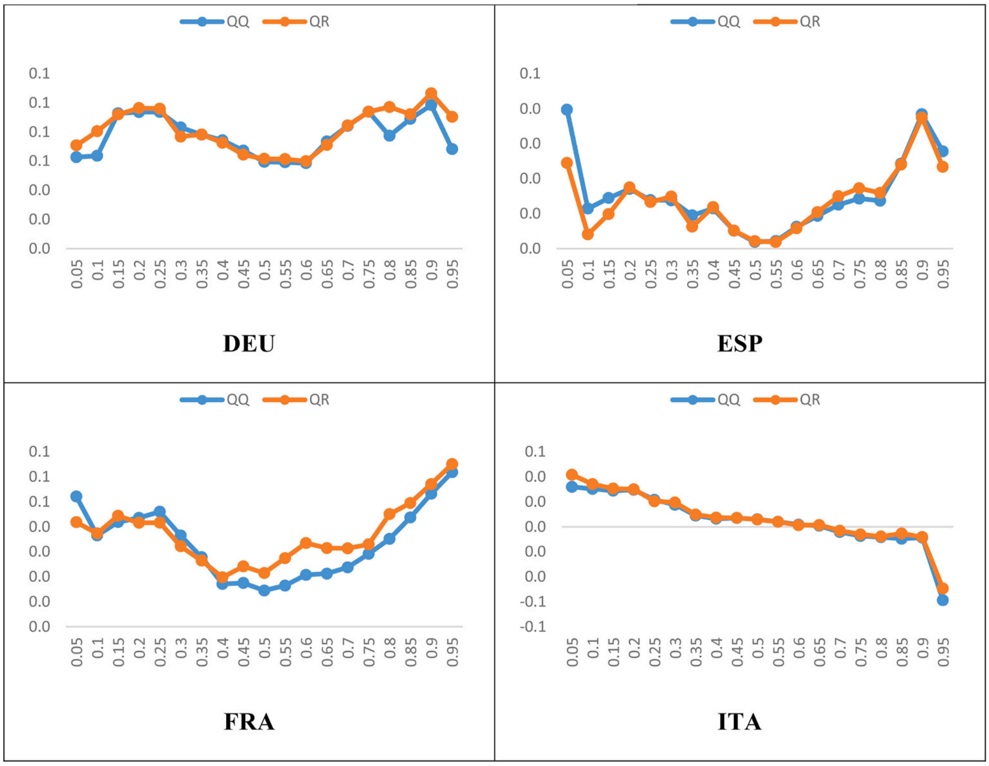
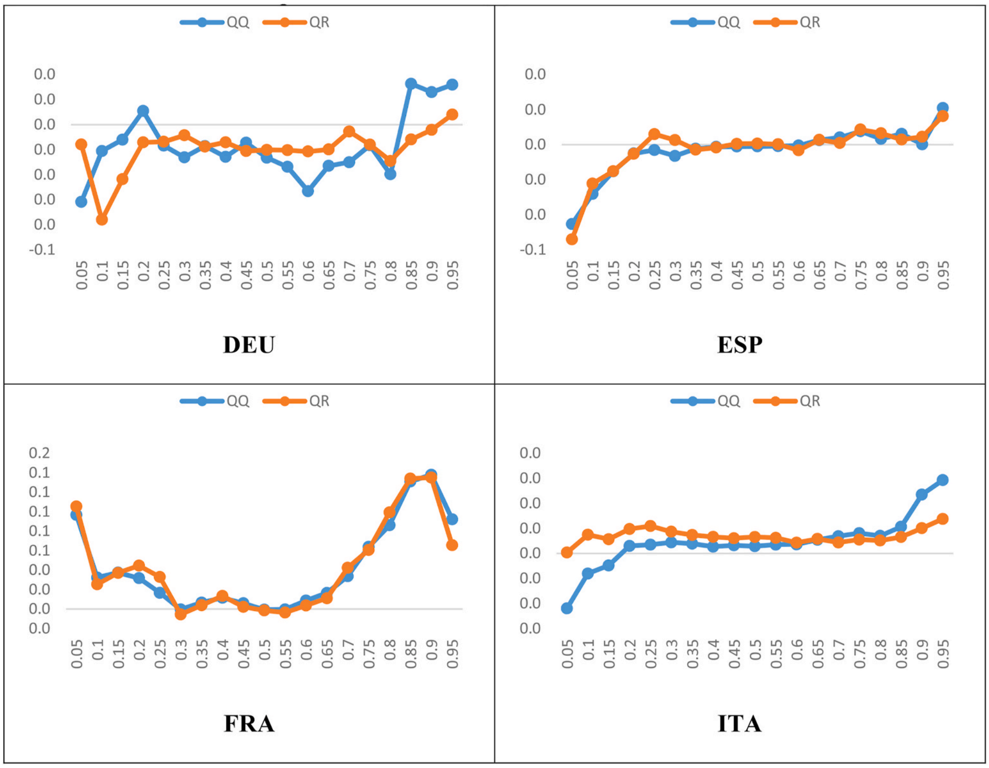
Annex 1. QQ and QR Comparison for COAL Effect on CO_2



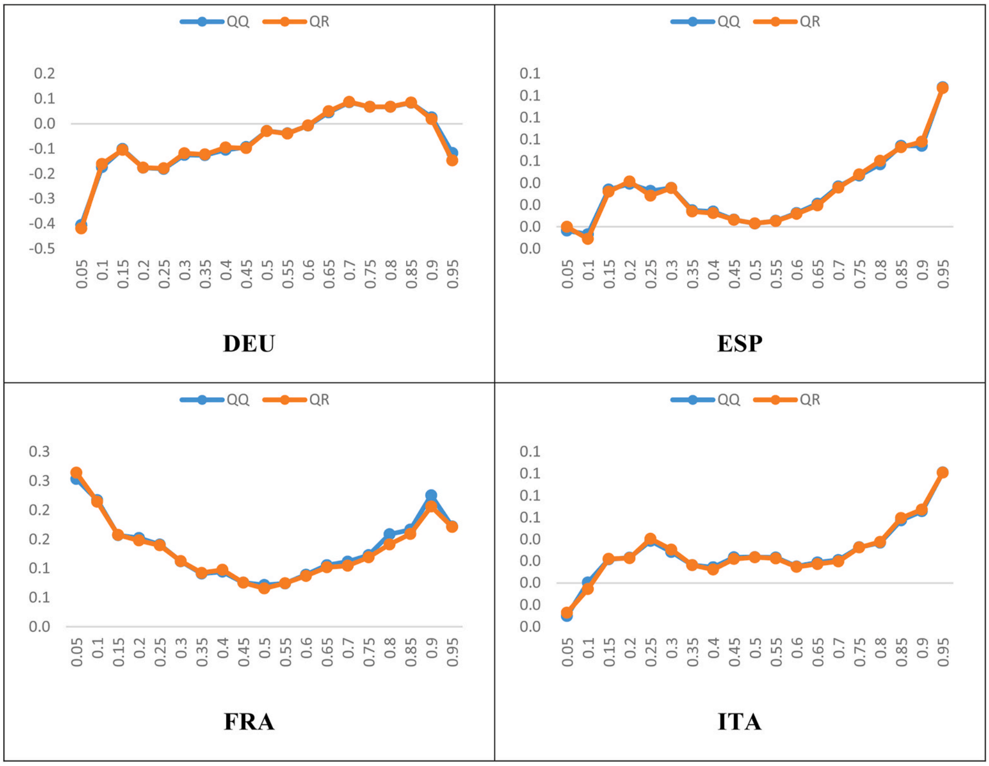
Annex 2. QQ and QR Comparison for GAS Effect on31 CO_2



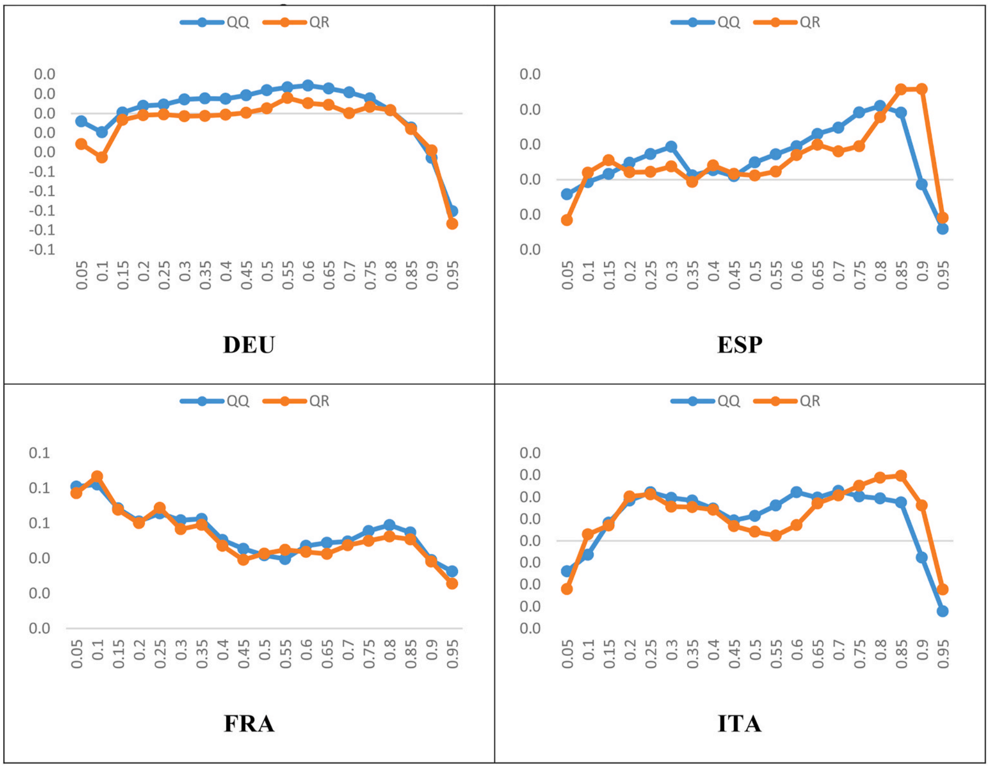
Annex 3. . QQ and QR Comparison for OIL Effect on CO_2



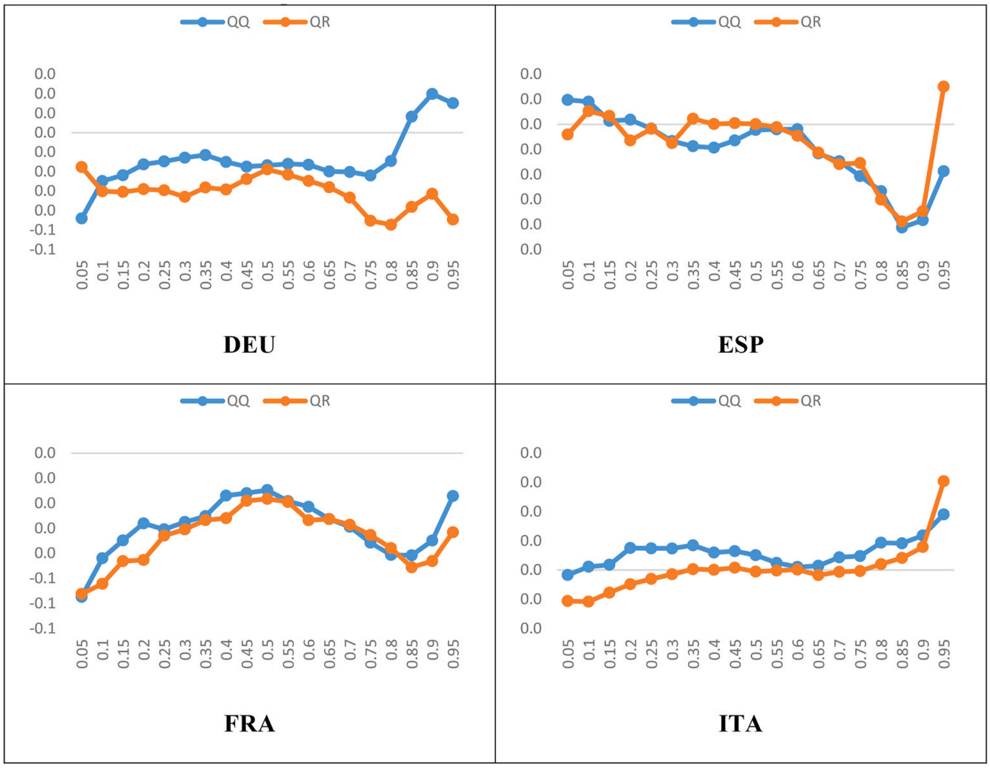
Annex 4. . QQ and QR Comparison for HYDRO Effect on CO_2



Annex 5. . QQ and QR Comparison for SOLAR Effect on CO_2



Annex 6. . QQ and QR Comparison for WIND Effect on CO_2



Nomenclature

Acronyms	
BDS	Broock, Scheinkman, Dechert, and LeBaron
EG	Electricity Generation
ELGH	Energy-Led Growth Hypothesis
EU	European Union
GHG	Greenhouse Gas Emissions
GQ	Granger Causality in Quantiles
QQ	Quantile on Quantile Regression
QR	Quantile Regression
Dependent Variable	
CO_2	CO_2 Emissions from the Residential Sector
Independent Variables	
COAL	EG from Coal
GAS	EG from Natural Gas
OIL	EG from Oil
HYDRO	EG from Hydro
SOLAR	EG from Solar
WIND	EG from Wind
Study Scope	
DEU	Germany
ESP	Spain
FRA	France
ITA	Italy

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