The impact of energy economics on environmental quality in Algeria during the period (2000-2022): using the kernel-based regularized least squares estimator (krls).

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Summary:
The objective of this study was to assess and quantify the environmental implications of various energy consumption indicators in Algeria, Four indicators (natural gas, coal, oil, and electricity) were used as independent variables to analyze the impact of energy use at a detailed level, CO2 emissions were used as a dependent variable reflecting environmental quality, using the Kernel-based regularized least squares (krls) method based on recent annual data available from 2000 to 2022.
The study results concluded a statistically significant positive impact of using coal, oil, natural gas, and electricity on CO2 emissions, demonstrating that the use of coal, natural gas, oil, and electricity, and coal leads to environmental quality degradation in Algeria.

Keywords: Energy indicators ; CO2 emissions; krls; Algeria.
Jel Classification Codes : P28 ; Q3 ; Q56.

I- Introduction :

Today, energy and environmental issues are among the topics that receive the greatest attention from governments, communities, and policymakers, due to their direct link to achieving sustainable development. It is impossible to produce or consume energy without impacting the environment to varying degrees, as energy production and consumption activities are the primary drivers of greenhouse gas emissions, foremost among them carbon dioxide (CO□), which contributes to climate change, global warming, and the degradation of air and water quality. In this global context, countries including Algeria face a dual challenge: meeting the growing demand for energy on one hand, and reducing environmental emissions and achieving climate targets on the other. This makes the search for effective solutions to reduce the intensity of greenhouse gas emissions, particularly carbon dioxide (CO□) emissions, essential for protecting the environment and safeguarding human health.

I.1. Problem:

Within the framework of sustainable development and based on this background, our research problem can be formulated as follows:

What is the impact of changes in energy indicators on environmental quality in Algeria?

I.2. The hypotheses:

To answer the previous questions, it is possible to start from number of uncertain hypotheses, which are as follows:

There is a statistically significant positive impact of natural gas consumption on CO2 emissions in Algeria

There is a statistically significant positive impact of electricity energy consumption on CO2 emissions in Algeria

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- There is a statistically significant positive impact of oil consumption on CO_2 emissions in Algeria.

- There is a statistically significant positive impact of coal consumption on CO_2 emissions in Algeria.

I.3. objectives:

This study aims to analyze the separate impact of key energy indicators, including electricity consumption, natural gas, oil, and coal, on environmental quality in Algeria during the period(2000-2022). The importance of this research stems from Algeria's national orientation towards sustainable energy policies and the reduction of its carbon footprint, as the country seeks to balance the growing energy demand with environmental preservation and the mitigation of carbon emissions. By examining the individual effects of energy indicators, the study seeks to provide accurate insights to support policymakers in making informed decisions that promote environmental sustainability. Furthermore, the study highlights the effectiveness of employing modern quantitative analytical methods, such as the Kernel-based Regularized Least Squares (KRLS) approach, to generate more precise and reliable estimates, thereby contributing to the formulation of evidence-based environmental energy policies.

I.4. Methodology and Tools:

In order to answer the problem at hand and test the validity of the hypotheses, the descriptive analytical approach was relied upon to diagnose the reality of energy as well as the evolution of the volume of carbon dioxide emissions in Algeria,

As for the applied aspect related to the standard study, which aims to show the quantitative impact of energy production indicators on environmental quality in Algeria, it relies on the quantitative inductive approach using models commensurate with the study data, the study employs the Kernel-based Regularized Least Squares (KRLS) method, which was selected for the following reasons:

- It does not assume linearity between variables, unlike methods such as OLS or ARDL.
- It does not require strict stationarity tests, making it suitable for short time series data in developing countries.
- It allows for the estimation of marginal effects for each variable at every data point, thereby uncovering heterogeneous relationships that conventional models may not capture.
- It is more reliable for supporting policy formulation compared to other machine learning techniques, which often face interpretability challenges or require large datasets.
- It has been scientifically validated as an effective tool in energy and environmental studies, according to recent literature.

The analysis was conducted using statistical software such as R, which provides the most comprehensive environment for implementing this methodology.

I.5. Previous studies:

Given the importance of energy revenues today in the global economy, and given its role in the emission of greenhouse gases, which is reflected in environmental quality, the global economy has become focused on achieving environmentally sustainable growth. Recent literature has focused on studying the role of energy in environmental quality, and among the most prominent of these studies we find:

- The study (Kanat et al., 2022) sought to measure the relationship between Russia's carbon dioxide emissions from 1990 to 2016 and the usage of coal, natural gas, and oil. Using the ARDL model, The findings indicate a long-term correlation between carbon dioxide emissions and coal, gas, and oil usage. Russia's increased use of coal, gas, and oil raises carbon dioxide emissions, which worsens the country's environmental conditions.

- The study (Shah et al., 2023) aimed to measure the impact of technology and natural gas supplies on carbon emissions in the 15 largest economies that depend on natural gas between the years 2000 and 2019. The long-term relationship between the specified variables was evaluated using the augmented mean group (AMG) estimator and the cross-sectional ARDL (CS -ARDL) estimator. The study's findings indicated that natural gas supply and technology had a negative effect on carbon emissions, which contributed to environmental sustainability.

- the study (Kartal et al., 2023), it studied the impact of energy consumption on carbon dioxide emissions in France during the period 1970-2021 using a distributed autoregressive model (DARDL), using the use of natural gas, nuclear energy, oil, and coal consumption as independent variables. Emissions of carbon dioxide, however, was the dependent variable. The study's conclusions showed a long-term relationship between energy consumption indicators and carbon dioxide emissions. The results also showed a positive, statistically significant correlation between carbon dioxide emissions and the usage of of natural gas, coal, and oil, while there was a negative effect of nuclear energy consumption on carbon dioxide emissions. In addition, DARDL simulation results show that positive shocks in nuclear power reduce CO2 emissions, Conversely, positive shocks to coal usage greatly raise CO2 emissions.

- A recent study by (Lin & Ullah, 2024b) discovered a negative correlation between carbon dioxide emissions with the expansion of nuclear and hydropower, and a positive correlation between carbon dioxide emissions and the increase of fossil fuel energy in Pakistan during the period 1975-2021, using DARDL, as The study concluded that positive and negative shocks in nuclear, coal and gas respectively caused significant short-term changes in carbon dioxide emissions, while their long-term effects remained stable.

As for Algeria, there is no study examining the separate impact of energy indicators represented by electricity, natural gas, oil and coal on environmental quality. Instead, studies focus on the impact of renewable or non-renewable energy on the environment. These studies lack future projections and rely only on correlation and regression studies. In contrast, our study uses novel estimation methods such as Kernel-based regularized least squares (krls) which provides more robust and reliable estimates when analyzing time series data, particularly in energy and environmental economics.

Table (1): Empirical literature summary.

Author	Scope	Period	Model	Result
(Kanat et al., 2022)	Russia	1990–2016	ARDL	gas → co2 (+) oil → co2 (+) coal → co2 +)
(Shah et al., 2023)	Top 15 natural gas supplier economies	2000–2019	AMG CS-ARDL	gas → co2 (-) gas → co2 (-)
(Kartal et al., 2023)	France	1970–2021	DARDL	gas → co2 (+) oil → co2 (+) coal → co2(+) Nuclear→ co2 (-)
(Lin & Ullah, 2024b)	Pakistan	1975–2021	DARDL	gas → co2 (+) oil → co2 (+) coal → co2 (+) Nuclear→ co2 (-) Hydro→ co2 (-)

Notes: ARDL: Autoregressive Distributed Lag; AMG: Augmented Mean Group ; CS-ARDL: Cross-Sectional ARDL; DARDL: Dynamic ARDL simulations; co2: CO emissions; gas: Natural Gas Energy Consumption; oil: Oil Energy Consumption; coal: Coal Energy Consumption; Nuclear: Nuclear Energy Consumption; Hydro: Hydro Energy Consumption.

The source : Prepared by the researchers.

The study is divided as follows: In the second section, We present a theoretical presentation on energy and carbon emissions in Algeria and their development since the year 2000. The study model, data specifics, and analytic methods are presented in the third part. The study's findings and analysis are covered in the fourth part. The fifth component, which wraps up the study, provides a summary of the findings and possible suggestions for energy policy in Algeria's framework of environmental sustainability.

II– Energy and Carbon Emissions in Algeria:

All countries worldwide strive to achieve the highest economic growth rates, and to meet the needs of economic development, humans have consumed massive amounts of fossil fuels, leading to the atmospheric emission of significant amounts of carbon dioxide (Zhao et al., 2022). Carbon dioxide is thought to be the dominating greenhouse gas and the primary cause of global warming. (Habib et al., 2021), which leads to environmental degradation and negatively impacts human health (Zhaohua Wang et al., 2019). The latter primarily results from human activities such as fossil fuel combustion (Gao et al., 2018), and with the serious increase in the global warming phenomenon, human life is adversely affected in various aspects, including loss of biodiversity, worsening food insecurity, increasing natural disasters, rising sea levels, and reduced crop production (Cai et al., 2023). Global climate change, primarily characterized by increased greenhouse gas emissions and rising average temperatures, has become one of the most prominent challenges facing agriculture in the twenty-first century (Shayanmehr et al., 2020). With the escalating effects of global climate change, global attention has shifted towards low-carbon economies and sustainable development (Wang et al., 2023).

Achieving environmentally sustainable economic growth is one of the most important and complex problems confronting policymakers, governments, and society in recent times. (Guesmi et al., 2023). Undoubtedly, global warming poses a significant threat, perhaps the greatest ever, endangering the planet (Delanoë et al., 2023). The Intergovernmental Panel on Climate Change (IPCC) said in its most recent report that "3.3 billion people will live in environments that could be at risk due to climate change by 2050." Consequently, efforts to reduce greenhouse gas emissions, particularly carbon dioxide (CO_2), have become an urgent the need and top priority for people, governments, and businesses to safeguard populations and economies at any costs (Lin & Ullah, 2024a). In this context, the Paris Agreement of 2015 set a very tangible goal: to control greenhouse gas emissions to limit global warming to 1.5 degrees Celsius, and emissions from electricity generation should be reduced to almost zero by the middle of this century by 2050 (IAEAgency).

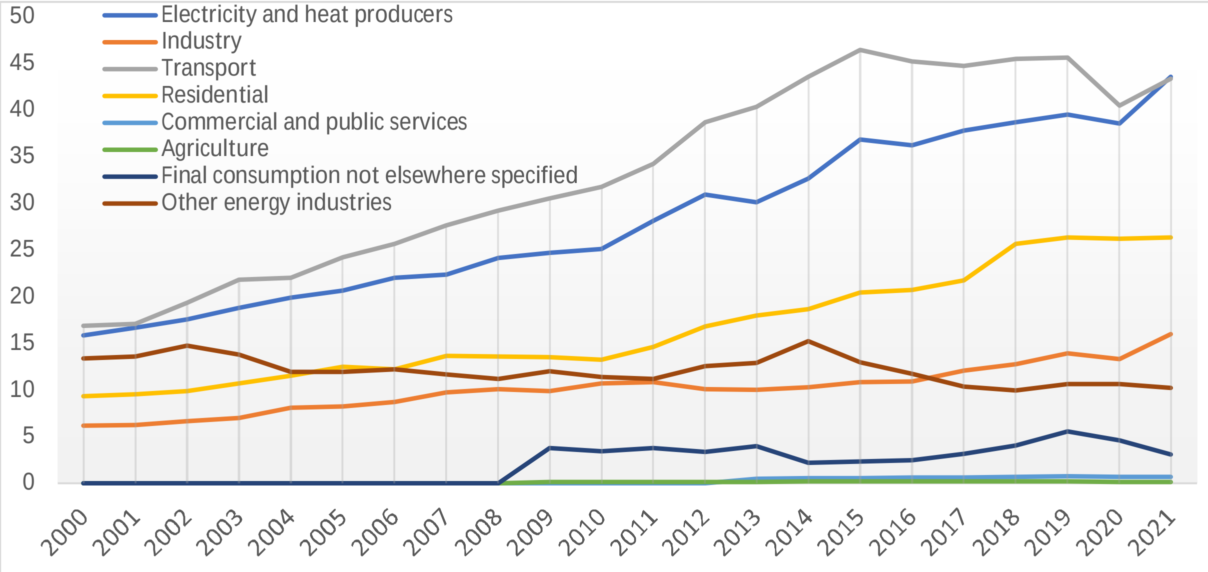
Generally, non-renewable energy sources and natural resources contribute to environmental pollution and pose risks to human health, such as cardiovascular diseases. Therefore, countries must work diligently to reduce reliance on these resources and prioritize the use of renewable alternatives in their economic activities (Yao et al., 2023). However, energy remains a key factor in the production process in most industries, making it difficult to reduce the use of this energy (Le, 2022). There is no escape from using energy to meet essential needs such as heating, lighting, transportation, and production (Kılıç Depren et al., 2022). For example, land transportation plays a prominent role in energy consumption for transportation and greenhouse gas emissions on a global scale (Peng et al., 2018).

According to a recent report issued by the International Energy Agency, Algeria's share of carbon dioxide emissions from combustible fuels for the year 2021 amounted to 0.43% of global emissions, ranking third in Africa and 32nd globally. Electricity generation accounts for 30.4% of carbon emissions in the country, while the transportation sector in Algeria accounts for approximately 30.2% of carbon emissions. Following that, the residential sector contributes around 18.3%, However, the industrial sector accounts for 11.1% of the nation's carbon emissions, while the remaining industries contribute 7.1%. Furthermore, how different sectors contributions to carbon dioxide emissions have changed throughout time

in Algeria can be tracked as follows:

The below figure illustrates a rise in carbon dioxide emissions across Algerian sectors over the research period, with the largest contributions coming from transportation and electricity production. It's noteworthy that there was a decrease in the contribution of the transportation sector in 2020, possibly due to the health measures imposed by the COVID-19 pandemic, including lockdowns and road travel restrictions to prevent infection, resulting in reduced car traffic and subsequently decreased carbon dioxide emissions. According to (Requia et al., 2018), reducing car usage, improving combustion efficiency, and employing low-emission vehicles may lead to a reduction in greenhouse gas emissions and prevent premature deaths due to air pollution associated with traffic congestion. Additionally, the housing sector has also witnessed a significant increase in carbon emissions in the country, rising from 9 metric tons in 2000 to 26 metric tons in 2021.

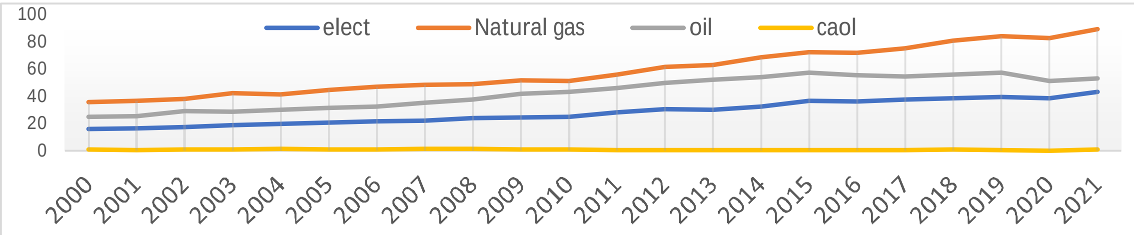
Figure (1): Evolution of CO_2 emissions by sector in Algeria since 2000.



The source : [IEA Data Services](#)

Furthermore, by tracking the evolution of carbon dioxide emissions volume brought on by the use of coal, oil, electricity, and natural gas in the figure below (Figure 02), it becomes apparent that CO2 emissions from natural gas consumption are the highest, followed by oil and electricity, with emissions from coal being relatively stable and very low.

Figure (2): Evolution power generation by source in Algeria since 2000.



The source: [IEA Data Services](#)

III– Methods and Materials:

III .1. Variables and data

The study utilized multivariate annual data from 2000 to 2022 in Algeria. As the energy indicators data is only accessible from 2000 onwards, while the study variables data extends until 2022, making the period from 2000 to 2022 our best period.

The study model and variables were formulated as follows:

$co2 = f(gas, coal, oil, elect)$

The dependent variable is environmental quality, which is expressed by the volume of carbon dioxide emissions (CO2), and energy consumption is studied in detail using four main indicators (natural gas, coal, oil, and electricity) as independent variables.

Moreover, table No. 2 briefly describes variables and data sources.

Table (2) : Variable's description and data sources.

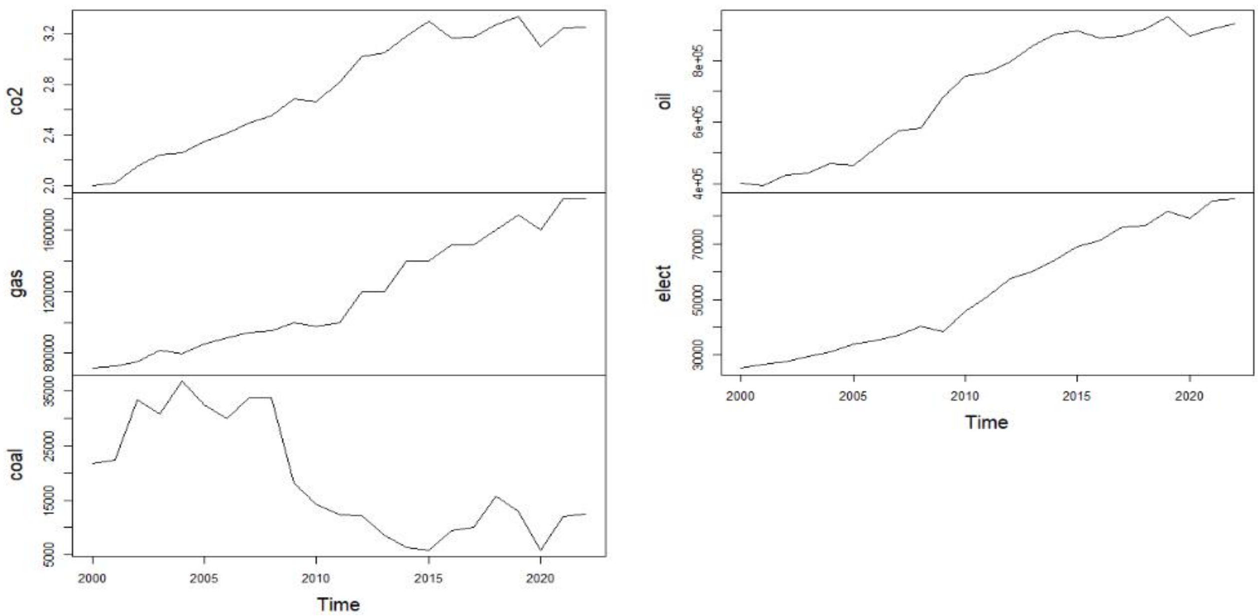
Parameters	Abbreviation	Unit	Source
CO2	CO2	Metric Tonnes (per capita)	IEA Data Services
Natural gas EC	Gas	Exajouls	IEA Data Services
Coal EC	Coal	Tonnes Joule	IEA Data Services
Oil EC	Oil	Tonnes Joule	IEA Data Services

Parameters	Abbreviation	Unit	Source
Electrical EC	elect	GWh	IEA Data Services

It is expected that there will be a significant increase in CO2 emissions with the rise in electricity production, natural gas, coal, and oil consumption.

We plot the evolution of each variable over time to reveal how the data has changed throughout time.

Figure (3): Trend analysis of variables.



The source: Prepared by researchers based on R software and IEA Data Services

From Figure 3 illustrating the evolution of study variables during the study period from 2000 to 2022, it appears that there is a positive trend in carbon dioxide emissions, natural gas, electricity, and oil. As for coal, it shows fluctuations with a noticeable decrease during the study period.

III .2. Methodology

To obtain a more powerful and reliable estimate, we evaluate the model using the Kernel-based regularized least squares (KRLS) method for time series data, which is gaining increasing interest in the field of energy and environmental economics(Lin & Ullah, 2024b). This algorithm is a standard economic machine learning technique that uses derivatives to examine the causal relationship between variables(Sarkodie & Owusu, 2020; Yi et al., 2023; Chen et al., 2024). This approach allows for the estimation of each independent variable's marginal impact on the dependent variable across points, and non-linear and non-homogeneous effects can be found by analyzing the distribution of these marginal effects. Additionally, this is achieved by calculating the average marginal effects (Pata et al., 2023; Adebayo, Özkan, et al., 2024;Iurgenson et al., 2024; Adebayo, Meo, et al., 2024).

The KRLS model, originally formulated by(J. Hainmueller & Hazlett, 2014), was primarily designed for social science researchers to conduct regression and inference without any prior assumptions of linearity or homogeneity (Ferwerda et al., 2017), indicating that the relationship between the independent and dependent variables is not subjected to arbitrary functional forms. It performs better than conventional econometric methods since there is no need for pre-testing the variables for stationarity (Byaro et al., 2024; (Mehboob et al., 2024). Additionally, KRLS enables researchers to interpret results in the same manner as traditional GLM regression models (Kartal et al., 2023). It can effectively estimate complex models with efficiency (Warsame et al., 2024). KRLS estimator carries favorable statistical characteristics, such as unbiasedness and consistency (Awan et al., 2022), and generates more flexible parameters compared to other machine learning techniques (Danish et al., 2023) such as neural networks and other machine learning methods developed and applied in social science inquiries. However, these methods have not been fully developed to handle social science data, reducing the reliability of their results and may not be suitable for policy formulation(Usman et al., 2024) , Unlike kernel-based regularized least squares methods, which are seen to be helpful and enhanced instruments for formulating time series policies (Choi & Lee, 2020; hou et al., 2022; Ozcan et al., 2023), as well as modeling and analytic problems including regression, model-based causal inference, and prediction problems, and regression(Alola et al., 2023; Hassan et al., 2023).

Accordingly, the Kernel-based Regularized Least Squares (KRLS) method is considered a modern tool for time series analysis, as it does not assume linearity or homogeneity among variables, making it well-suited for complex datasets in energy and environmental economics. This methodology allows for the estimation of marginal effects for each variable at every data point, thereby revealing non-linear and heterogeneous relationships. Moreover, it does not require stationarity tests and provides more precise and reliable estimates compared to conventional methods. KRLS results are easily interpretable, similar to traditional regression models, and possess strong statistical properties such as unbiasedness and consistency. Therefore, KRLS represents an effective and enhanced tool for formulating time series-based policies.

The expression that follows might be used to estimate KRLS using equation number (02):

$$co2_t = \Omega_1 gas_t + \Omega_2 coal_t + \Omega_3 oil_t + \Omega_4 elect_t + \varepsilon_{it} \ldots (02)$$

Where Ω1 to Ω4 represent the average estimated marginal effects based on KRLS for each data point.

IV- Results and discussion :

IV.1. Descriptive analysis:

The characteristics of the variables are presented in Table 03, From this Table, it is evident that the average emission of carbon dioxide during the study period was estimated at 2.771 tons with a standard deviation of 0.455 tons. The lowest value was recorded in the year 2000, while the highest value was observed in 2019. As for natural gas and electricity, their lowest values were recorded in 2000, while their highest values were observed in 2022. Regarding coal, its lowest value was recorded in 2020, estimated at 5894 tons of Joules, which coincided with the spread of the coronavirus pandemic. The highest ratio was recorded in 2004. Finally, concerning oil in Algeria, the highest ratio was in 2019, equivalent to 942353 tons of Joules, while the lowest ratio was estimated at 393359 tons of Joules in 2001. These ratios show less dispersion in terms of carbon dioxide emissions and more dispersion concerning natural gas, coal, oil, and electricity.

Table (3) : Summary statistics.

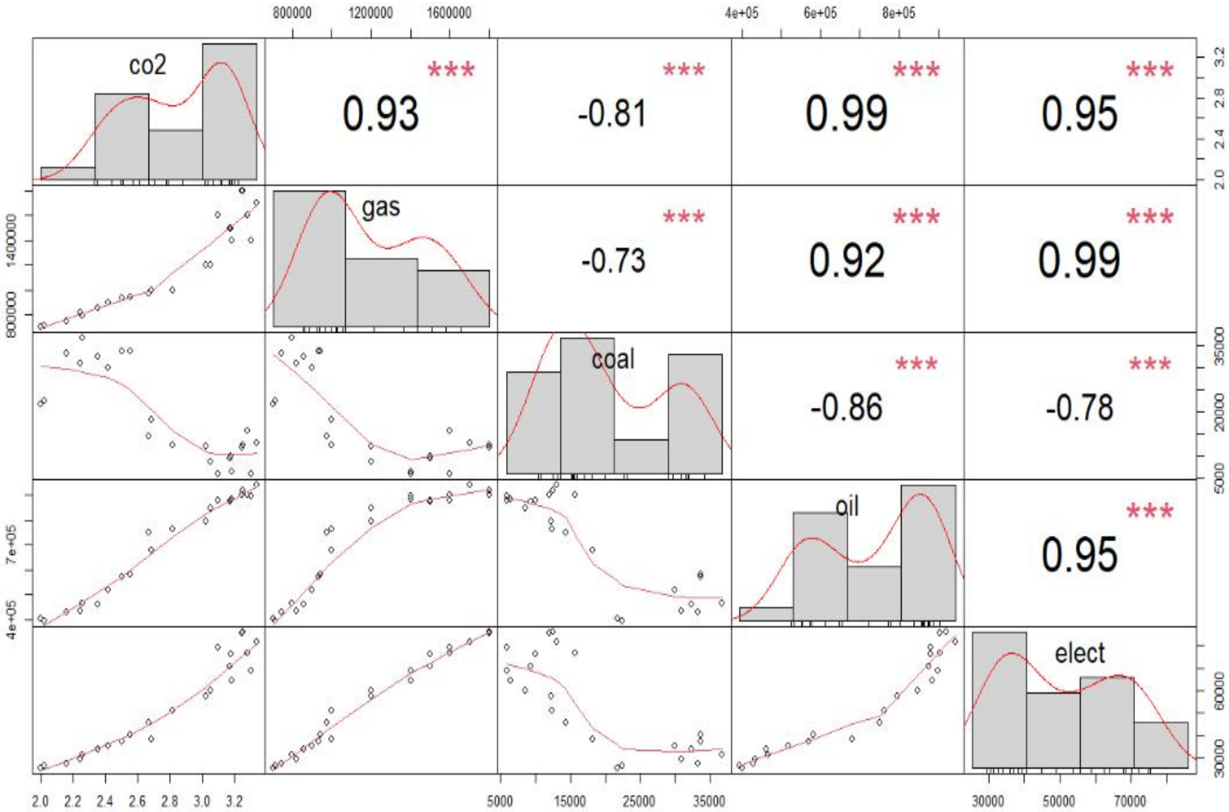
Variable	Obs.	Mean	Std. Dev.	Min	Max
CO2	23	2.771	0.4552238	1.999	3.333
gas	23	1178220	369457.6	705024	1800000
Coal	23	18762	10538.76	5894	36744
Oil	23	703391	202308.3	393359	942353
elect	23	53418	21286.7	25412	85999

The source: Prepared by researchers based on R software output.

IV.2. Correlation relationships between variables:

To evaluate the quality of the relationship between energy indicators and environmental quality in Algeria, we performed the correlation analysis in Figure 4 for each variable with the other variables graphically, using Pearson correlation coefficients, which are between -1 and +1, The correlation's strength is shown by a number that is near to +1 or -1. Using the figure's results, it is evident that there is a strong positive relationship between CO2, natural gas, electricity, and oil, while coal is negatively correlated with carbon dioxide emissions (CO2).

Figure (4): The study's variables' correlation structure.



Notes: The diagonal displays the distribution of each variable. Below the diagonal: bivariate scatter plots with a fitted line are presented showing the direction of the relationship. Above the diagonal: Correlation values and their significance levels are displayed above the diagonal, denoted by stars. ***, **, and * are significant at 1%, 5%, and 10%, respectively.

The source: Prepared by researchers based on R software output.

IV.3. The KRLS estimation results:

The results of estimating the influence of energy indicators on environmental quality in Algeria using kernel-based regular least squares (KRLS) are presented in Table 4. The results below reveal the average marginal effect of natural gas, coal, oil, and electricity is 0.1678%, 0.0297%, 0.1125%, and 0.0579% respectively. These parameters were statistically significant at 1%, demonstrating the significance of these factors in raising Algeria's carbon dioxide emissions. Additionally, the results show the significance of the KRLS model at 1%, with a variance explained of 0.9939, meaning that 99.39% of the variance in environmental quality, expressed by the volume of carbon dioxide emissions, can be predicted by the regression applied in this study (KRLS). Thus, the results of Kernel-based regularized least squares (KRLS) estimation indicate that all electricity, natural gas, coal, and oil have positive effects on carbon dioxide. The marginal effects are examined in their quarters (P25, P50, and P75), where the marginal effects of electricity, natural gas, coal, and oil increase from low quarters to high quarters. This highlights the role of gas, coal, oil, and electricity in increasing the level of carbon dioxide emissions and thus contributing to the deterioration of environmental quality in Algeria.

Table (4) : Results with the KRLS models.

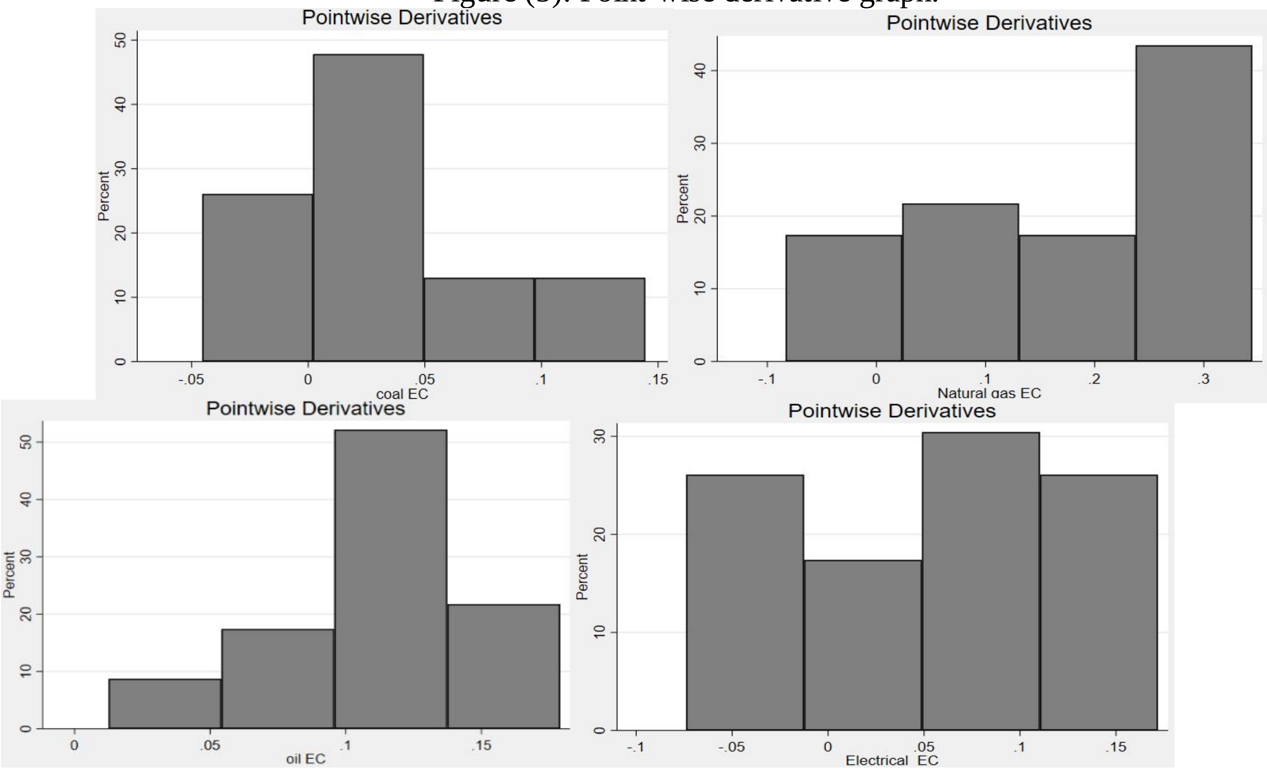
CO2 emissions	Average	SE	t	p > t	P25	P50	P75
gas	0.1678	0.0212	7.9165	0.000	0.0546	0.2189	0.2842
Coal	0.0297	0.0102	2.9129	0.009	-0.0034	0.0219	0.0478
Oil	0.1125	0.0213	5.2818	0.000	0.0957	0.1225	0.13240
elect	0.0579	0.0176	3.2871	0.004	0.0011	0.0770	0.1115
Diagnostics							
Lambda	0.0689	Sigma	4	R2	0.9939	Obs.	23
Tolerance	0.023	Eff. Df	9.216	Looloss	0.7069		

Notes: Avg. is the average marginal effect; SE is the standard error; P25, P50 and P75 represent the marginal influences in the first quarter, second quarter (median), and third quarter respectively, ***, **, * Significant at 1%, 5%, and 10% respectively, ; co2 : CO emissions; gas: Natural Gas Energy Consumption; oil: Oil Energy Consumption; coal: Coal Energy Consumption; elect: electricity Energy Consumption.

The source: Prepared by researchers based on R software output.

Fig. 5 shows the gaz, coal, oil, and elect point-wise derivatives normal distribution graph using (KRLS). The natural gas is positively skewed, while coal and oil is normally distributed, whereas electrical ec are positively and negatively skewed.

Figure (5): Point-wise derivative graph.

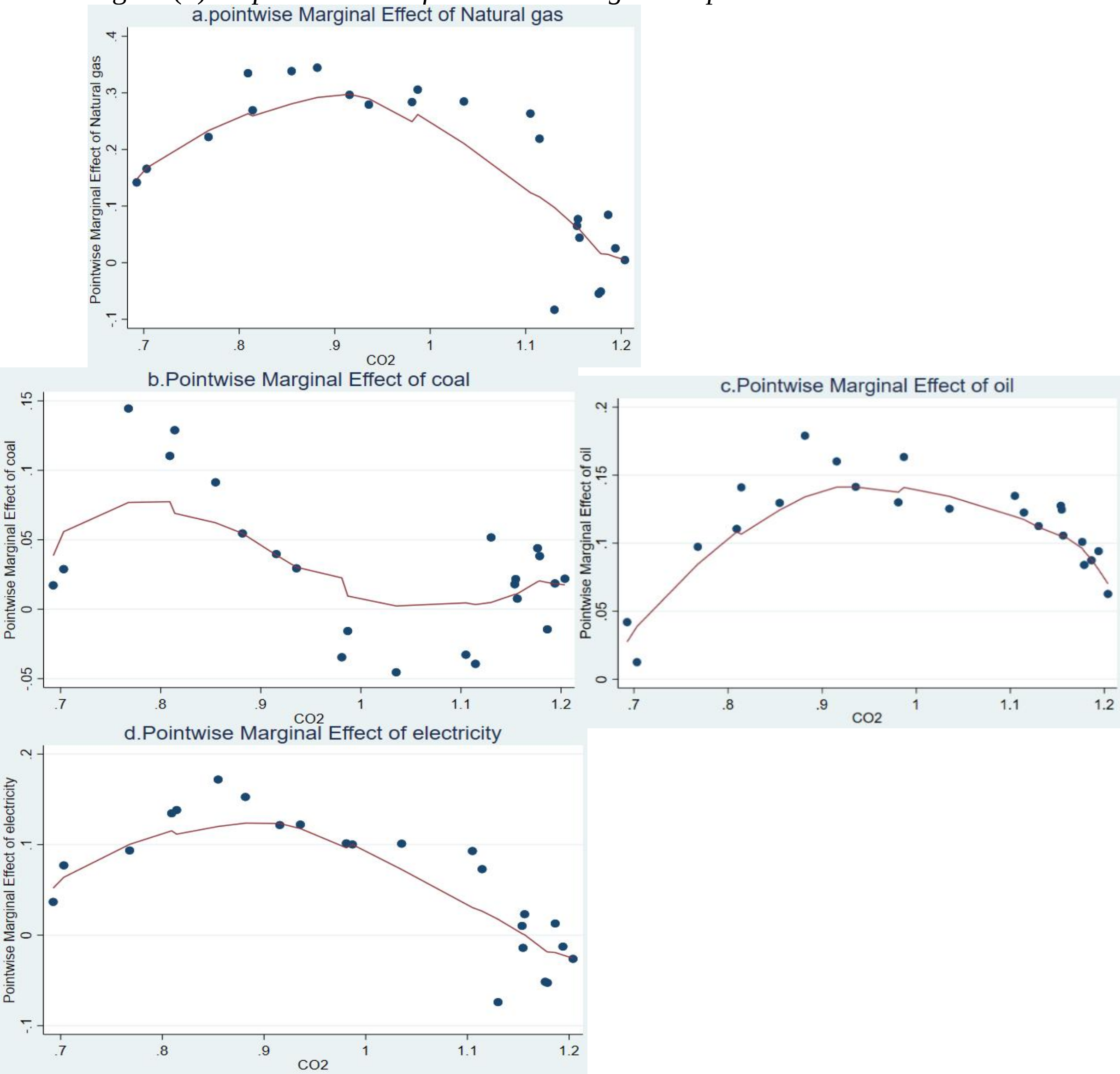


The source: Prepared by researchers based on Stata 17 software

For further detail on how changes in energy will impact environmental quality in the future, we are conducting an analysis of the long-term effects of energy indicators (gas, coal, oil, and electricity) by plotting the derivative of gas, coal, oil, and electric towards CO2 emissions to obtain various marginal effects, The results are illustrated in Figure 6, where Figure 6a indicates that an increase in natural gas rates leads to higher carbon dioxide emissions at lower levels up to a threshold where marginal returns are enhanced, but later, gas reduces carbon dioxide emissions.

Additionally, team (c) demonstrates that oil significantly increases CO2 emissions up to a certain point, then continues to increase with diminishing marginal returns. Similarly, team (d) shows that electricity increases CO2 emissions up to a certain extent, while the supporting effect of electricity on environmental quality weakens in the long run with decreasing marginal returns. While higher levels of natural gas, oil, and electricity raise carbon dioxide emissions at higher levels beyond the baseline, diminishing marginal returns occur. Finally, Figure 6b illustrates the marginal returns of coal, showing that higher coal levels consistently affect carbon dioxide emissions from the threshold point where marginal returns exist, but later exhibit a surge in CO2 emissions towards emissions.

Figure (6): *Representation of Pointwise marginal impact on CO2.*



The source: Prepared by researchers based on Stata 17 software.

V- Conclusion and discussion:

V.1. Conclusions:

To study the effects of changes in various subcomponents of energy consumption on environmental quality in Algeria, the following four indicators (natural gas, coal, oil, and electricity) were used as independent variables to analyze the impact of energy use at a disaggregated level, while CO2 emissions were used as a dependent variable representing environmental quality, using the Kernel-based regularized least squares (KRLS) approach, newly proposed based on recent annual data available from 2000 to 2022.

The results of employing the KRLS approach indicate a statistically significant positive impact of coal, oil, natural gas, and electricity use on CO2 emissions, confirming that energy consumption leads to environmental degradation in Algeria, This validates the four hypotheses of the study: "There is a statistically significant positive impact of natural gas consumption on CO2 emissions in Algeria",' "There is a statistically significant positive impact of electricity energy consumption on CO2 emissions in Algeria", "There is a statistically significant positive impact of oil consumption on CO2 emissions in Algeria," and "There is a statistically significant positive impact of coal consumption on CO2 emissions in Algeria".

Accordingly, the results indicate that Algeria's energy structure being almost entirely based on fossil fuel sources remains the most influential factor driving CO_2 emissions. The increase in natural gas consumption can be explained by the partial shift toward gas in the industrial sector; however, this transition has not been accompanied by effective measures to improve energy efficiency or reduce emissions. In contrast, the consumption of oil and coal is mainly associated with the transport sector and heavy industry, both of which are well-known for their substantial contribution to carbon emissions.

Furthermore, the findings related to electricity show that its production and consumption, despite the noticeable expansion, still rely almost entirely on gas fired power plants. Therefore, electricity in Algeria cannot be considered a "clean" energy source from an emissions standpoint, unlike in many economies that rely on renewable energy sources.

The findings of this study which confirmed the presence of a positive and statistically significant effect of natural gas, coal, oil, and electricity consumption on carbon dioxide emissions in Algeria are consistent with a substantial portion of the economic and environmental literature, while some differences remain attributable to the structure of the energy mix and the economic contexts of the countries under comparison.

- The study by (Kanat et al., 2022), which examined the relationship between CO_2 emissions and the consumption of coal, natural gas, and oil in Russia during the period 1990–2016, reported a long-term relationship among these variables and showed that increased consumption of fossil fuel energy sources leads to higher CO_2 emissions and environmental degradation. These findings directly align with the results of the present study, as both studies demonstrate that heavy reliance on fossil fuels significantly increases carbon emissions. Despite the economic differences between Algeria and Russia, the negative role of fossil energy remains consistent in both cases.

- In contrast to the results of this study, (Shah et al., 2023) applied to the 15 largest natural-gas-dependent economies found that natural gas supply and technological advancement contributed to reducing CO_2 emissions in the long run. This divergence stems from fundamental differences in technological infrastructure within those economies, which possess highly efficient technologies and a more advanced energy sector that enables improved gas utilization and reduced emissions. In Algeria, however, despite the expansion in natural gas use, the absence of effective policies aimed at improving energy efficiency has caused increased gas consumption to be associated with higher emissions, thereby explaining the discrepancy between the two studies.

- The study by (Kartal et al., 2023) indicated a long-term relationship between energy consumption indicators and CO_2 emissions in France from 1970 to 2021, showing a positive and statistically significant effect of natural gas, coal, and oil consumption on emissions, alongside a negative effect of nuclear energy consumption. These findings are in line with the present study's results regarding fossil fuel sources, reinforcing the positive association between fossil energy consumption and emissions across different contexts. However, the key point of divergence is that Algeria does not rely on nuclear energy, thus lacking a low-emission source that France possesses. Consequently, Algeria's energy mix remains predominantly fossil-based, which explains the stronger positive impact on emissions.

- The study by (Lin & Ullah, 2024b) in Pakistan (1975–2021) found a negative relationship between CO_2 emissions and the expansion of nuclear and hydropower, and a positive association between emissions and fossil fuel energy expansion. The present study aligns with the segment related to fossil energy, as the effect of conventional fuel consumption remains positive on emissions.

The negative impact of nuclear and hydropower in Pakistan, however, cannot be directly compared with Algeria due to the absence of nuclear energy and the limited contribution of hydropower, which leaves Algeria more vulnerable to rising emissions as long as its energy mix remains fossil-fuel dominated.

Accordingly, the comparison shows that the findings of this study are largely consistent with the majority of the literature pointing to the detrimental environmental effects of fossil fuel consumption in both developed and developing countries. The discrepancies observed with certain studies such as (Shah et al., 2023) are primarily attributed to differences in technological advancement, energy efficiency levels, and the diversification of the energy mix across countries.

Thus, fossil energy remains the most critical factor driving environmental degradation, highlighting the need for policy interventions aimed at improving energy efficiency and transitioning toward cleaner and less polluting energy sources.

Furthermore, the impact of energy consumption changes on long-term CO2 emissions was also examined by plotting derivative points. It was found that both electricity, natural gas, and oil significantly increase CO2 emissions up to a certain point, then continue to increase with diminishing marginal returns. As for the effect of coal on CO2 emissions, higher coal levels consistently affect carbon dioxide emissions from the threshold point where marginal returns exist, but later exhibit a surge in CO2 emissions towards emissions.

Accordingly, this study provides a set of important theoretical contributions, the most notable of which are:

- Reinforcing the importance of disaggregated energy consumption analysis, which allows for accurately identifying the most polluting energy sources—an added value to the literature that often relies on estimating the effects of aggregate energy consumption.
- Providing new empirical evidence supporting the fossil energy–environmental degradation hypothesis, which posits that economies dependent on conventional fuels face difficulties in improving environmental quality without undertaking structural reforms.

From a practical perspective, the results highlight the urgent need for a comprehensive review of Algeria’s energy policies. Continuing to rely heavily on fossil fuels will maintain CO□ emissions at elevated levels, hindering the achievement of environmental quality.

V.2. Policy suggestions:

Based on the study results, the following recommendations can be made:

- Efforts should be focused on reducing carbon dioxide emissions to ensure a sustainable future, in addition to stepping up efforts in Algeria to encourage the use of renewable energy sources like nuclear and hydroelectric electricity and reduce the country's reliance on fossil fuels. Nuclear energy plays an effective role in reducing carbon dioxide emissions and can contribute to revolutionizing the energy sector, being essential for achieving sustainable economic growth and improving human welfare.
- New generation capacity must be provided to replace old fossil fuel units, especially those relying on coal, to meet the increasing demand for electricity and reduce carbon dioxide emissions.
- Accelerating the transition toward renewable energy sources, particularly solar energy, in which Algeria possesses vast and largely underutilized potential.
- Promoting innovation and scientific research in the field of clean energy, and strengthening collaboration between universities and industry to support the energy transition.

V.3. Limitations and future directions:

Although this study has established a methodological theoretical framework and employed a robust standard model to assess the impact of energy economics on environmental quality in Algeria by analyzing the separate effects of key energy indicators, including electricity, natural gas, oil, and coal consumption it still faces several research limitations. These limitations, in turn, represent a fertile ground and promising opportunities for future research, through which the scope of analysis can be expanded and the understanding of the relationships between energy indicators and environmental quality can be deepened, thereby enriching the scientific literature and supporting the development of more accurate and contextually appropriate models in this field.

Study Limitations

1 .Data limitations: This study relies on annual data for energy indicators and environmental emissions during the period 2000–2022. While this timeframe provides a suitable general overview, the use of higher-frequency data (quarterly or monthly) could allow for a more precise understanding of short-term dynamics and sudden changes in energy consumption and emissions.

2 .Focus on key energy indicators: The study concentrates on electricity, natural gas, oil, and coal consumption, without including other energy sources such as renewable energy (solar, wind) or emerging technologies, which may limit the comprehensiveness of the environmental impact assessment.

3 .Limited scope of the study: The research focuses exclusively on Algeria, allowing for an in-depth understanding of energy-environment interactions at the national level. However, the findings may not be directly generalizable to other countries with different energy structures or environmental policies.

Future Research Directions

1 .Inclusion of renewable energy sources and emerging technologies: Future studies could expand the scope of analysis to examine the impact of renewable energy adoption, energy efficiency, and emerging technologies on environmental outcomes, thereby enhancing the comprehensiveness of the research.

2 .Use of higher-frequency or cross-sectional data: Employing quarterly or monthly data, or extending the study to include multiple countries in the Middle East and North Africa (MENA) region, could improve the understanding of both short-term and long-term dynamics.

3 .Integration of socio-economic variables: Examining the interaction between energy consumption and environmental quality alongside socio-economic factors such as industrialization, urbanization, and population growth can provide a more holistic view of human activity's impact on the environment.

4. Inclusion of additional environmental variables: Considering factors such as desertification and forest fires, and analyzing their effects on environmental quality, rather than focusing solely on the hydrocarbon sector, would broaden the scope of environmental risk analysis.

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