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Impacts of renewable and non-renewable energy on CO_2 emissions in Egypt's electricity Generation: A K-nearest neighbor approach

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Abstract

This paper employs the K-Nearest Neighbor (k-NN) algorithm to examine the relationship between electricity generation—using renewable and non-renewable energy sources—and carbon dioxide (CO_2) emissions. The model achieved strong predictive accuracy, with a mean squared error (MSE) of 134.9 and an R^2 value of 0.915. Two analytical approaches were applied: the first included both renewable and non-renewable energy sources to determine the largest contribution of each energy source, and the second excluded non-renewable sources to assess the relative importance of different types of renewable energy. In the first approach, fossil fuel-fired electricity generation contributed 98.04% of the impact on carbon dioxide emissions, confirming its dominant role in increasing global carbon emissions. Renewable energy sources, however, had limited contributions: solar (1.16%), wind (0.71%), hydropower (0.09%), and bioenergy showed a negligible impact. In the second approach—excluding fossil fuels—renewable energy sources gained relative importance, with wind energy emerging as the most influential factor in the model (80.24%), followed by solar (10.92%), and hydropower (8.84%). Bioenergy remained insignificant in both models. The study concludes that fossil fuel–based electricity generation remains the principal driver of CO_2 emissions globally. though, among renewable sources, wind energy exhibits the greatest potential for reducing emissions when fossil fuels are excluded, highlighting its strategic importance in future clean energy transitions. The findings confirm the need for global energy policies that prioritize expanding renewable energy infrastructure, particularly solar and hydropower, while phasing out reliance on fossil fuels. countries should focus on stimulating investment in clean energy, developing efficiency-enhancing technologies, and expanding renewable energy generation to achieve long-term carbon reduction and environmental sustainability while maintaining economic growth.

Keywords: CO_2, Electricity generation, Emissions, K-Nearest neighbor algorithm, Non-renewable energy, Renewable energy.

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1. Introduction

Climate change represents a significant global challenge, primarily driven by carbon dioxide (CO_2) emissions from human activities, particularly in the energy sector. This problem highlights the effects of both renewable and non-renewable energy sources on electricity generation and their roles in CO_2 emissions. To create sustainable energy policies that harmonize environmental protection and economic development, it is essential to grasp the connection between Egypt's electricity generation energy mix and CO_2 emissions.

Recent studies suggest that adopting renewable energy sources, such as solar, wind, and hydropower, can reduce carbon emissions compared to traditional fossil fuel-based energy production [1, 2]. The ability of these sources to decrease CO2 emissions depends on several factors, including their contribution to total electricity production, technological efficiency, and the state of infrastructure [3]. Therefore, researchers, energy, and environmental regulators can gain valuable insights into how various energy sources impact CO2 emissions by employing sophisticated analytical techniques, such as the K-Nearest Neighbor (KNN) method.

This study examines the impact of various electricity generation sources in Egypt—fossil fuels (GWh), bioenergy (GWh), hydropower (GWh), solar energy (GWh), and wind energy (GWh)—on the country's CO_2 emissions (in metric tons of CO_2e). Utilizing quantitative data, the research assesses the distinct impacts of each energy source using the K-nearest neighbor (KNN) model. This machine-learning technique predicts future values based on patterns in historical data.

The KNN model excels at classifying data based on distances within the variable space, enabling a more profound understanding of the patterns related to CO_2 emissions in Egypt and their links to electricity generation from various sources [4]. This model evaluates the impact of each energy source on emissions and offers policy recommendations, informed by empirical evidence, to guide the energy sector toward sustainable practices.

Egypt presents a fascinating case study because both population growth and economic development fuel its increasing electricity demand. Despite efforts to improve the use of renewable energy, electricity generation from fossil fuels, measured in gigawatt-hours (GWh), remains the primary source of power in the country [5]. This situation necessitates a comprehensive assessment of the balance between various energy sources and their environmental impacts. To inform the development of national energy policies aimed at reducing Egypt's carbon footprint in the future, this study provides a comprehensive scientific analysis of the impact of various energy sources on Egypt's CO_2 emissions, measured in metric tons of CO_2.

This research investigates the impact of various energy sources on CO2 emissions in Egypt, measured in metric tons. It includes electricity generated from fossil fuels, bioenergy, hydropower, solar energy, and wind power. The study highlights the benefits of transitioning to renewable energy sources to reduce emissions. Furthermore, it assesses the performance of the K-Nearest Neighbor model in forecasting CO_2 emission levels based on the energy generation mix. By addressing these topics, the study aims to lessen the environmental impacts of electricity generation while providing quantitative, data-driven insights into Egypt's energy landscape and its role in sustainable development.

2. Literature review

There is significant agreement among global and regional studies about the role of renewable energy in reducing CO_2 emissions. A survey conducted by Abdallah and El-Shennawy [6] in Egypt modeled three energy scenarios, showing that a "green scenario" (which prioritizes solar, wind, and hydro power) could decrease emissions to 128 million tons by 2030, compared to the 307–330 million tons projected with continued fossil fuel use. In a similar vein, Metwally, et al. [7] assessed the effects of Egypt's Benban Solar Park, uncovering an annual reduction of 2 million tons of CO_2, which is comparable to removing 400,000 cars from the streets.

Turedi and Turedi [8] conducted a global analysis involving 45 developing countries, revealing that a 1% rise in renewable energy use leads to a 0.12% decrease in CO_2 emissions. This conclusion aligns with the research by Rahman, et al. [9] which demonstrated that renewable energy sources significantly reduce emissions in fossil fuel-reliant nations, such as Egypt. Furthermore, regional studies, such as the analysis by Alharthi, et al. [10] employed quantile regression on MENA countries, indicating that renewable energy significantly influences emissions reduction in regions with elevated emissions.

Voumik, et al. [11] reinforced this in G7 nations, where the replacement of coal and gas with renewables resulted in an 18–22% reduction in emissions.

Non-renewable energy sources, particularly coal and natural gas, are consistently linked to rising CO_2 emissions. Abdallah and El-Shennawy [6] cautioned that if Egypt continues to rely on fossil fuels, emissions could increase to 330 million tons by 2030. Conversely, Farhani and Shahbaz [12] noted a different trend in the MENA region: despite economic growth, the increased reliance on fossil fuels has led to rising emissions. On a global scale, Zoundi [13] employed panel cointegration methods to demonstrate that fossil fuels are a significant contributor to emissions, thereby undermining the benefits of renewable energy. Similarly, Arshad, et al. [14] reported that in South and Southeast Asia, emissions from non-renewable energy sources rose by 0.8% for every 1% increase in consumption.

Adebayo and Beton Kalmaz [15] reported that fossil fuels account for 89% of Egypt's electricity generation, suggesting that emissions primarily stem from energy use rather than urban growth. Furthermore, Espoir, et al. [16] noted that Africa's reliance on fossil fuels leads to "emission lock-ins," prompting Egypt to reduce its dependence on natural gas.

Egypt is recognized for its bold renewable energy ambitions. Salah, et al. [17] established a goal to attain 42% renewable energy by 2035, emphasizing the opportunities provided by solar and wind sources. Elkelawy, et al. [18] explored Egypt's initiative known as the "solar revolution," which plans to generate 2 GW from CSP/PV systems by 2030, potentially resulting in a 15–20% decrease in emissions. Farnoosh and Lantz [19] supported the inclusion of nuclear energy, predicting a decline of 25 million tons of CO_2 each year.

However, challenges persist. Rashdan and Ibrahim [20] linked rapid urbanization to a 6% annual rise in electricity demand, straining fossil fuel-dependent grids. Ibrahim [21] warned that Egypt's emissions could rise by 125% between 2012 and 2035 if the use of renewable energy is not encouraged. Farhani and Shahbaz [12] highlighted a transitional paradox: hybrid systems are crucial, as the early adoption of renewable energy may cause a brief spike in emissions due to grid instability.

Innovations in technology are crucial for Egypt's transformation. According to Abdallah and El-Shennawy [22] the implementation of smart grids can improve the integration of renewable energy and decrease system losses by 12%. Granovskii, et al. [23] noted that in desert regions like Egypt, hybrid solar/wind-hydrogen systems could lower emission reduction costs by 30%. According to Gibson et al. (2024), if 53% of energy comes from renewable sources by 2030, it's estimated that 732 million tons of CO2 emissions could be avoided by 2070.

Policies necessitate well-defined frameworks. Shouman [24] argued in favor of feed-in tariffs, emphasizing that solar energy represents an affordable substitute for power in rural areas. Kuri and Li [25] noted that 20% of investments in renewable energy could be directed toward a carbon tax of $30 per ton, highlighting the significance of carbon pricing in accurately estimating emission costs. According to Al-Riffai, et al. [26]. Egypt should gradually phase out fossil fuel subsidies, which currently account for 4–6% of the nation's annual GDP.

Comparative studies provide valuable insights for Egypt and ASEAN. Liệu and Thạch [27] linked non-renewable energy sources to increased emissions, advocating for policies to limit coal growth. EU: BUȘU and BUȘU [28] demonstrated that renewable subsidies resulted in a 14% reduction in EU emissions.GCC: Despite investments in solar energy, Abdallah and El-Shennawy [6] found that emissions increased by 0.9% for every 1% rise in oil and gas consumption. Baratta [29] warned that unless robust policies are implemented, solar energy's global contribution may remain below 2% by 2050, jeopardizing Egypt's solar-centric policy.

Contradictions and Research Gaps: Although many studies support the effectiveness of renewable energy, Farhani and Shahbaz [12] found that the consumption of both renewable and non-renewable energy initially increased emissions in the MENA region, likely due to transitional grid inefficiencies. Namahoro, et al. [30] found that the effects of economic growth on emissions differ by region, complicating policy design.

Significant research gaps exist in technological scalability. El Safty and Siha [31] emphasized the necessity for lifecycle assessments (LCAs) of solar and wind projects in Egypt to evaluate their long-term sustainability. Rashdan and Ibrahim [20] emphasize the importance of research that integrates innovative municipal strategies to reduce urban energy consumption in their study on Urbanization Dynamics. Considering the economic trade-offs, Kuri and Li [25] emphasized the need for cost-benefit analyses to align with Egypt's 2030 renewable energy objectives.

3. Data Section

This study uses annual data from 2000 to 2022 to examine the impact of various energy sources on CO_2 emissions in Egypt. The dataset comprises independent variables collected from the International Monetary Fund (IMF) and a dependent variable sourced from the World Bank.

Table 1.
Variable Description.

In Dependent Variables	Electricity Generation from Bioenergy (GWh)	Measures the amount of electricity produced from biomass-based energy sources.
	Electricity Generation from Fossil Fuels (GWh)	Represents electricity generated from conventional fossil fuel sources such as coal, oil, and natural gas.
	Electricity Generation from Hydropower (GWh)	Captures electricity produced from hydroelectric power plants.
	Electricity Generation from Solar Energy (GWh)	Reflects electricity output from solar photovoltaic (PV) and other solar power systems.
	Electricity Generation from Wind Energy (GWh):	Represents the electricity generated from wind farms and wind turbines.
Dependent Variable	Egypt's CO_2 Emissions	is measured in metric tons of CO_2 equivalent (Mt CO_2e)

Table 2.
Data statistics.

Variables	Source of Data	Mean	Mode	Median	Dispersion	Minimum	Maximum
CO2 emissions	World Bank	208.6	127.9	219.3	0.19	127.9	262.07
Electricity Generation from Bioenergy	IMF	316.6	235.6	316.4	0.072	235.6	356.3
Electricity Generation from Fossil Fuels	IMF	135052	56322.8	1466407.8	0.30	56322.8	190114.6
Electricity Generation from Hydropower	IMF	13598.7	12859	131210	.068	12644	15510
Electricity Generation from Solar Energy	IMF	793.8	1.006	25.4	2.006	0.168	5003.06
Electricity Generation from Wind Energy	IMF	1646.2	93.44	1272.40	0.93	93.44	5677.4

The data is organized in an annual time series format, which ensures consistency and comparability among different energy sources. Including various electricity generation sources enables a thorough evaluation of their individual effects on CO_2 emissions.

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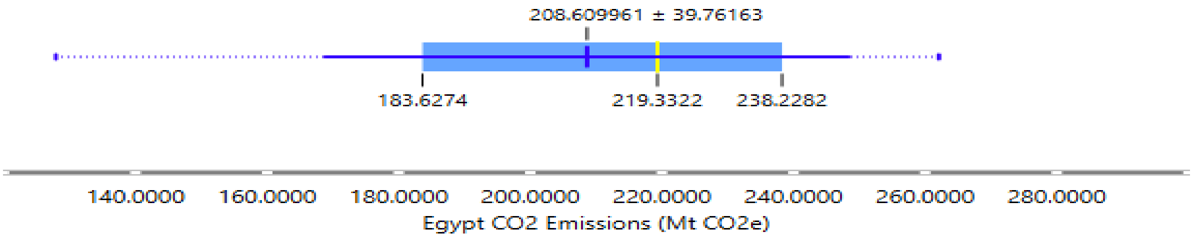

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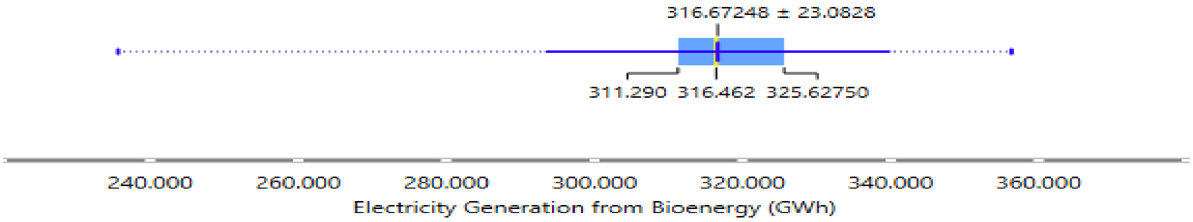

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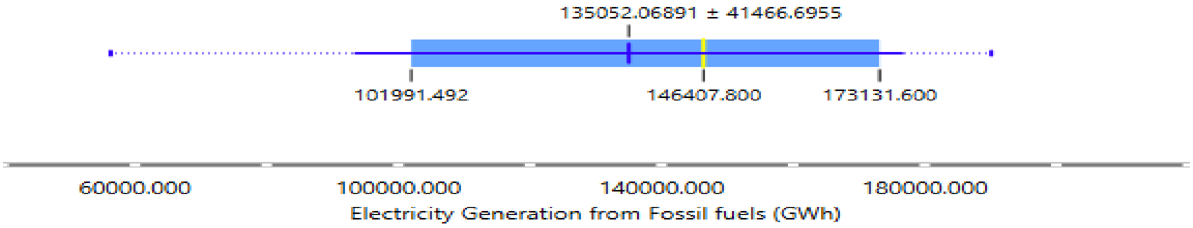

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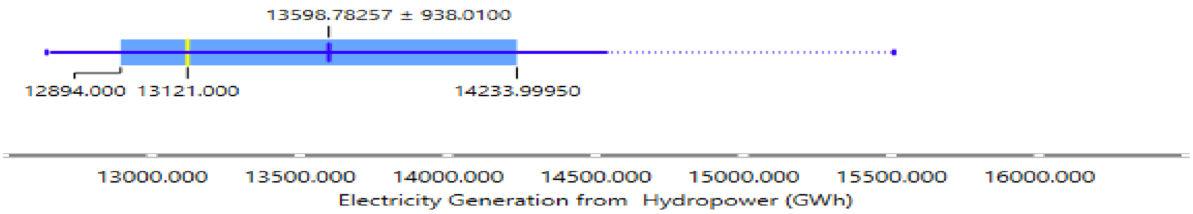

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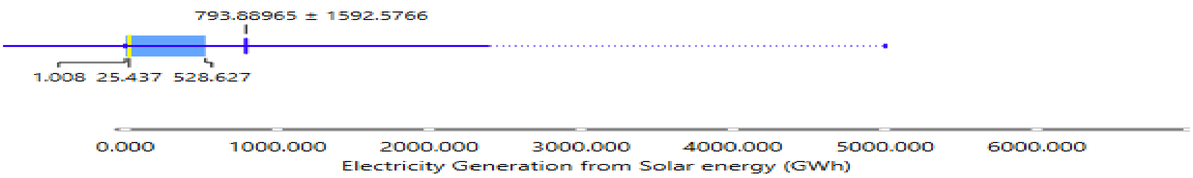

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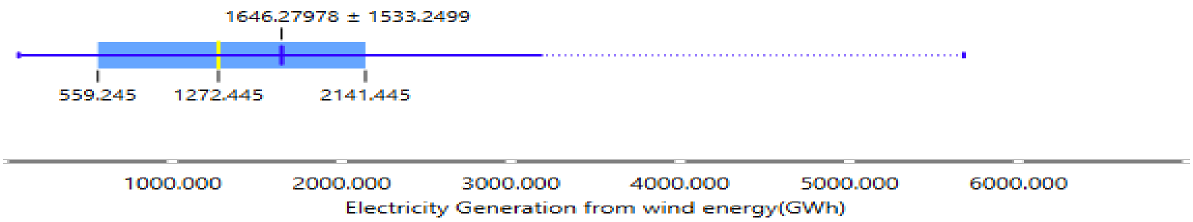


Figure 1.
variables Box plot.

The initial plot shows Egypt's CO_2 emissions, with an average of about 208.6 million tons of CO_2, ranging from 140 to 280 million tons of CO_2. Although there is some variation, the data do not exhibit significant skewness.

Regarding electricity generation from different energy sources, fossil fuels dominate with the highest average production (approximately 135,052 GWh) and the broadest range of variation, reflecting Egypt's significant reliance on this source. In comparison, the generation of electricity from solar and wind resources remains relatively low and exhibits significant fluctuations, as illustrated in their graphs. Hydropower, on the other hand, demonstrates more excellent stability, maintaining a narrower range around its average output, which suggests consistent production without drastic fluctuations. Despite its increasing popularity, wind energy still lags behind fossil fuels and is highly variable, primarily due to the unpredictability of wind resources.

In conclusion, the boxplots highlight Egypt's significant reliance on fossil fuels, as well as its ongoing but insufficient efforts to transition to renewable energy sources.

4. Methodology

A well-liked instance-based, non-parametric machine learning method for applications involving regression and classification is KNN. KNN utilizes the average values of the K closest data points in the feature space to predict a continuous target variable in regression scenarios. Because it is predicated on the idea that neighboring data points have similar properties, this approach facilitates the handling of complex and nonlinear datasets [4].

4.1. Distance Metrics

KNN regression evaluates related data points using a selected distance measure. The distance functions that are most commonly utilized are as follows:

- Euclidean Distance:

$$d(x_i, x_j) = \sqrt{\sum_{k=1}^{n} (x_{ik} - x_{jk})^2}$$

- Manhattan Distance:

$$d(x_i, x_j) = \sum_{k=1}^{n} |x_{ik} - x_{jk}|$$

- Minkowski Distance (Generalized Form):

$$d(x_i, x_j) = \left(\sum_{k=1}^{n} |x_{ik} - x_{jk}|^p\right)^{\frac{1}{p}}$$

The model's performance is significantly influenced by the choice of distance measures, depending on the type of data being analyzed.

4.2. Prediction Function in KNN Regression

The forecasting value $\hat{y}$ is determined using the following formula for a new data point after the K-nearest neighbors have been determined:

$$\hat{y} = \frac{1}{K}\sum_{i=1}^{K} y_i$$

Where $\hat{y}$ refers to the target values of the K nearest neighbors.

In contrast, distance-weighted KNN regression assigns greater weights to near neighbors:

$$\hat{y} = \frac{\sum_{i=1}^{K} w_i y_i}{\sum_{i=1}^{K} w_i}$$

Where the weight w_i is commonly believed to be the reverse of distance:

4.3. Model Evaluation Metrics

Several error measurements are used to evaluate KNN regression's performance:

- Mean Squared Error (MSE):

$$MSE = \frac{1}{n}\sum_{i=1}^{n} (y_i - \hat{y}_i)^2$$

- Root Mean Squared Error (RMSE):

$$RMSE = \sqrt{MSE}$$

- Mean Absolute Error (MAE):

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |y_i - \hat{y}_i|$$

- R-squared (R^2):

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2}$$

A lower MSE or RMSE, along with a higher R^2 value, suggests superior model performance, as shown in Table 3.

Table 3.
The ML algorithms' prediction.

Model	MSE	RMSE	MAE	R2
KNN	134.9	11.61	9.63	0.915
GB	140.31	11.84	9.7	0.911
RF	182.5	13.5	10.9	0.885
DT	183.03	13.5	11.6	0.884
SVM	700.5	26.46	21.55	0.55
NNs	1222	34.9	21.08	0.227

The performance indicators used to evaluate various machine learning models for forecasting CO2 emissions in Egypt are presented in Table 3. These metrics—Mean Squared Error (MSE), Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and R^2 (coefficient of determination)—assess how effectively the models represent the variability in CO_2 emissions.

Among the models tested, KNN (k-Nearest Neighbors) stands out as the best performer, recording the lowest MSE of 134.9 and RMSE of 11.61. It also boasts a high R^2 score of 0.915, which demonstrates substantial predictive accuracy. Furthermore, it has the most petite MAE of 9.63, indicating that its predictions are the most precise on average. Close behind is Gradient Boosting (GB), which exhibits slightly higher error metrics but maintains a comparable R^2 value of 0.911, marking it as a solid alternative.

Random Forest (RF) and Decision Trees (DT) exhibit moderate performance, with R^2 values of 0.885 and 0.884, respectively, demonstrating a decrease in accuracy. They show more significant errors compared to KNN and GB, suggesting that these models may be less effective at generalizing when predicting CO_2 emissions.

In contrast, Support Vector Machines (SVM) and Neural Networks (NNs) perform notably worse. SVM records an R^2 value of 0.55, reflecting limited predictive capacity, whereas NNs yield the lowest results with an R^2 of 0.227, indicating difficulties in recognizing patterns in the data. Additionally, the elevated MSE (1222) and RMSE (34.9) underscore their lack of effectiveness in this scenario.

KNN is the most successful model overall, achieving the best balance between reducing errors and maximizing prediction accuracy. GB ranks second. While SVM and NNs have difficulty producing accurate predictions, RF and DT perform moderately well.

4.4. KNN Prediction Performance

This step evaluates the KNN prediction performance by comparing Egypt's actual CO2 emissions values with the KNN prediction values, as shown in Table 4 and Figure 2.

Table 4.
Actual CO_2 Emissions in Egypt versus kNN Prediction Values.

year	Egypt's CO2 Emissions actual values (Mt CO2e)	kNN prediction
2000	127.9103	144.466
2001	141.1988	144.466
2002	144.9575	144.466
2003	147.8503	164.095
2004	160.4135	164.095
2005	178.3832	175.494
2006	188.8716	186.327
2007	201.9517	196.311
2008	202.0152	202.984
2009	210.3349	209.076
2010	211.7459	215.274
2011	219.3322	220.619
2012	232.9413	225.17
2013	228.7388	232.841
2014	233.0930	242.17
2015	239.3925	242.17
2016	250.0974	242.17

2017	262.0766	246.866
2018	256.5749	248.969
2019	237.0639	246.328
2020	226.1884	245.498
2021	249.7365	246.328
2022	247.1607	243.345

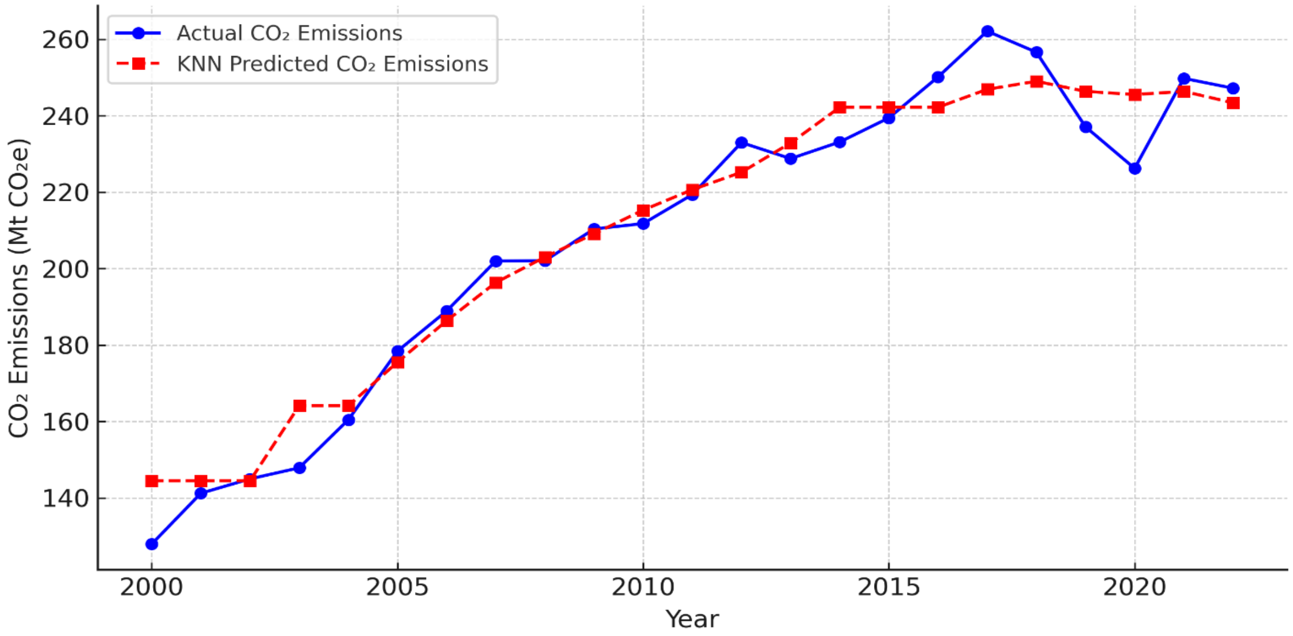


Figure 2.
Actual CO2 Emissions values in Egypt versus kNN prediction values.

The graph compares actual CO_2 emissions in Egypt (2000-2022) with KNN-predicted values. The exact emissions show a steady increase, while KNN predictions struggle to capture early trends, remaining constant from 2000 to 2004. As emissions continue to rise, the model's accuracy improved between 2005 and 2015, although occasional overestimations occur.

Between 2016 and 2022, KNN predictions increasingly matched actual values, yet they struggled to capture sudden shifts, such as the drop from 2019 to 2020. This issue stems from KNN's assumption that historical trends will repeat, making it less effective in responding to rapid changes caused by economic policies and other outside influences.

While KNN offers a reasonable estimate of long-term trends, its accuracy may decrease during times of significant fluctuations. By employing more flexible models, such as Random Forest or LSTM, predictions can be enhanced by considering additional variables that affect emissions.

4.5. KNN Feature Importance

This critical step involves assessing how independent variables affect dependent variables in two different models: Model 1 incorporates both non-renewable and renewable energy. In contrast, Model 2 focuses exclusively on renewable energy by excluding non-renewable sources. The effects are detailed in Tables 5 and 6.

Table 5.
KNN feature importance (model 1: including non-renewable energy).

Feature	**Score**
Electricity Generation Bioenergy	0
Electricity Generation: Fossil fuels	98.04427
Electricity Generation Hydropower	0.090404
Electricity Generation: Solar energy	1.160734
Electricity Generation wind	0.706765

Table 6.
KNN feature importance (model 2: excluding non-renewable energy).

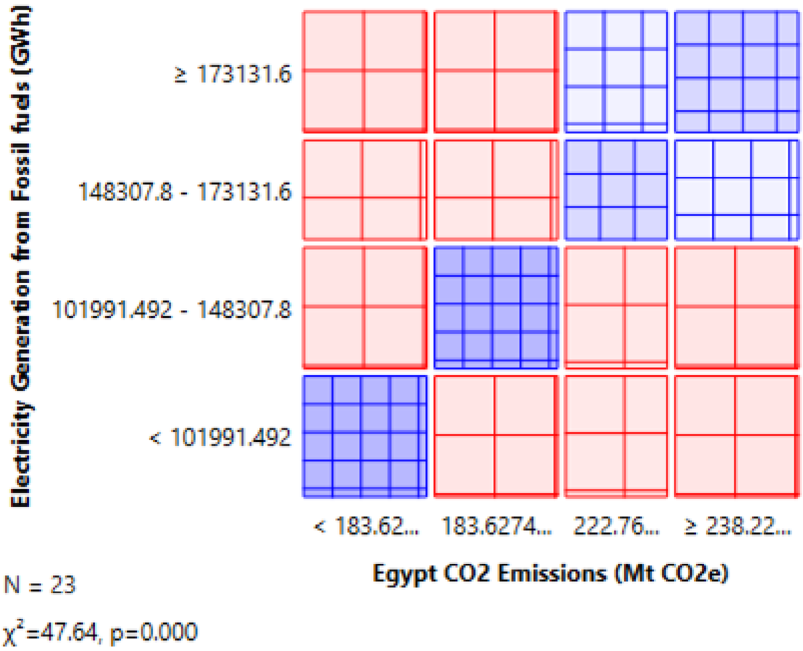
Feature	**Score**
Electricity Generation from Bioenergy	0
Electricity Generation from Hydropower	8.84492533
Electricity Generation from Solar Energy	10.9161231
Electricity Generation from Wind Energy	80.2404755

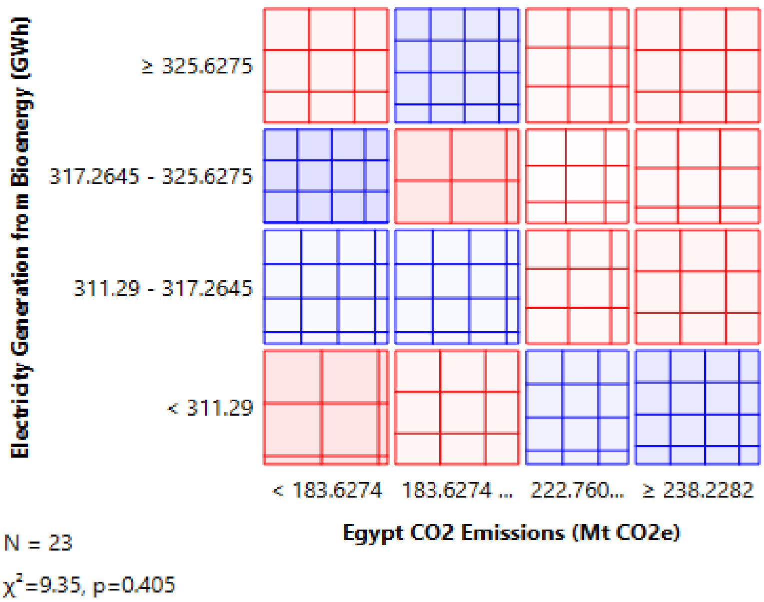
The results of feature importance from the two KNN models demonstrate how different energy sources impact CO_2 emissions, with the inclusion of non-renewable energy having a significant influence.

In Model 1, which incorporates fossil fuels, the data reveal that fossil fuel electricity generation (98.04%) significantly leads the predictions, highlighting its dominant role in CO_2 emissions. Conversely, renewable sources, such as hydropower (0.09%), solar (1.16%), and wind (0.71%), contribute very little, with bioenergy making no significant impact. This suggests that the presence of fossil fuels outweighs the effects of renewable energy sources on emissions.

In Model 2, which omits fossil fuels, the significance of renewable energy sources is emphasized. Wind energy (80.24%) is the primary contributor, followed by solar energy (10.92%) and hydropower (8.84%), while bioenergy has a minimal impact. This suggests that among renewable energy sources, wind power has a significant effect on changes in CO_2 emissions.

When considered as a whole, the apparent discrepancy between the two models underscores the substantial impact of fossil fuels on CO_2 emissions. In contrast, wind energy is the most prominent renewable energy source when fossil fuels are not used. This implies that wind and solar energy are expected to play a significant role in reducing emissions as the world transitions to renewable energy sources. Please refer to Figure 3's sieve diagram to gain a better understanding of this relationship.





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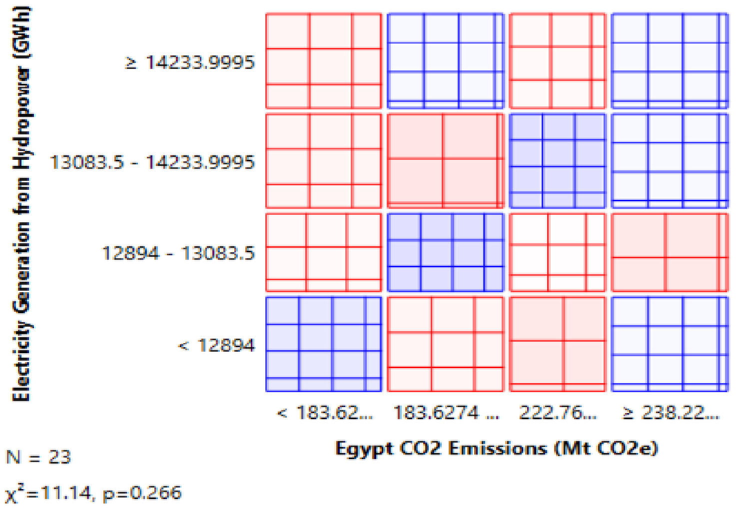
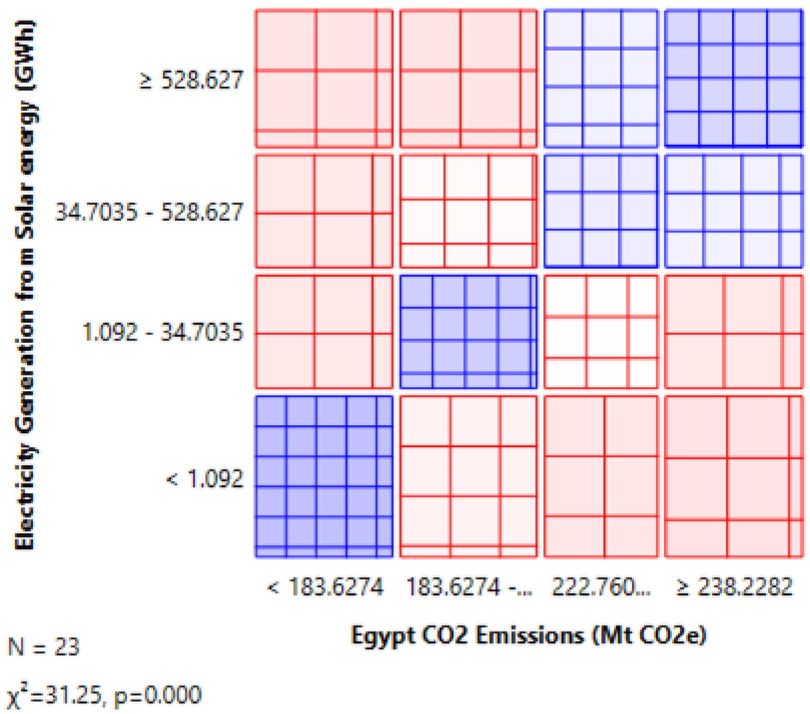

Electricity Generation from Hydropower (GWh)
≥ 14233.9995
13083.5 - 14233.9995
12894 - 13083.5
< 12894
< 183.62...
183.6274 ...
222.76...
≥ 238.22...
Egypt CO2 Emissions (Mt CO2e)
N = 23
χ²=11.14, p=0.266


Electricity Generation from Solar energy (GWh)
≥ 528.627
34.7035 - 528.627
1.092 - 34.7035
< 1.092
< 183.6274
183.6274 -...
222.760...
≥ 238.2282
Egypt CO2 Emissions (Mt CO2e)
N = 23
χ²=31.25, p=0.000

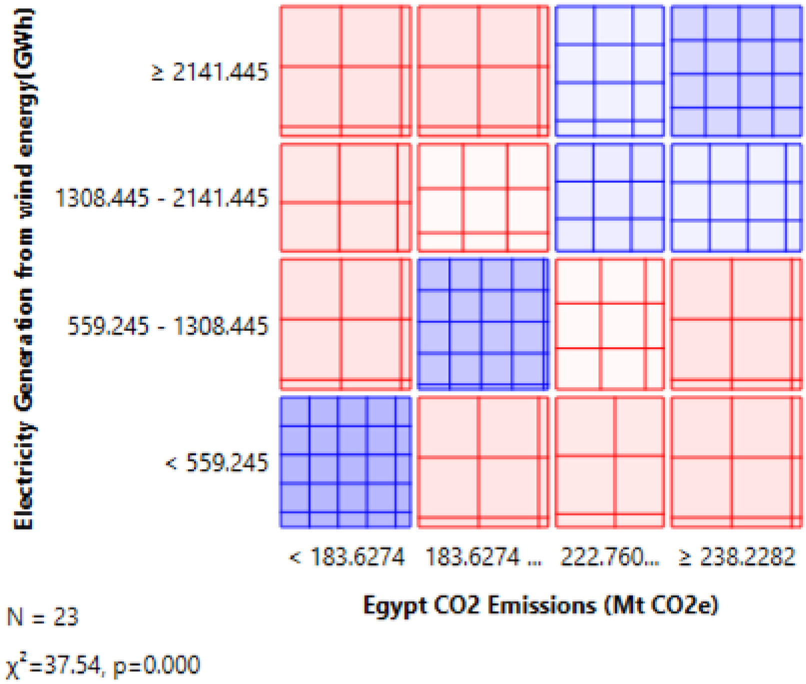


Figure 3.
The sieve diagram shows the relationship of the variables.

The charts illustrate the relationship between electricity generation from various sources in Egypt and CO_2 emissions. The most substantial and most statistically significant relationship exists between fossil fuel-based electricity generation and carbon emissions. This is supported by the Chi-square test value ($\chi^2 = 47.64$, $p < 0.000$), which indicates a direct relationship between increased reliance on fossil fuels and higher CO_2 emissions. The consistent appearance of red squares in the chart highlights this issue, illustrating the uneven distribution of carbon emissions across various levels of fossil fuel electricity generation.

In contrast, the relationship between hydroelectric power generation and CO_2 emissions appears statistically insignificant, evidenced by a Chi-square value of 11.14 and a p-value of 0.266. This implies that hydropower's effect on carbon emissions is either minimal or indirect. The chart's color distribution supports this conclusion, showing no evident patterns that suggest a strong correlation between the two variables.

The analysis reveals a significant association between solar and wind energy and CO_2 emissions, as indicated by Chi-square values of 31.25 ($p = 0.000$) for solar energy and 37.54 ($p = 0.000$) for wind energy. This implies that rises in electricity generation from these sources correlate with variations in carbon emissions, although the specifics of this relationship warrant additional study. This link may be affected by fluctuations in energy demand or Egypt's energy mix, where conventional power plants may be utilized to offset fluctuations in renewable energy production.

The results show no significant statistical relationship between biomass energy and CO_2 emissions ($\chi^2 = 9.35$, $p = 0.405$). This implies that biomass energy likely has a minimal impact on emission levels, or its effect may be slight and influenced by other factors not included in the analysis.

The findings indicate that a majority of carbon emissions in Egypt's electricity sector are attributed to the use of fossil fuels. Conversely, biomass and hydropower contribute only minimally. Moreover, while wind and solar energy are renewable resources, their connection to carbon emissions is complex, necessitating further study to understand their significance in Egypt's energy transition fully.

5. Conclusion

This study highlights the essential roles of both renewable and non-renewable energy sources in CO_2 emissions in Egypt's electricity sector. The results indicate that fossil fuel-based electricity generation is the primary source of CO_2 emissions, stressing the urgent need for effective energy transition strategies. The potential of renewable energy sources, such as solar and wind, which could drastically reduce emissions, is hindered by Egypt's reliance on non-renewable energy. This study highlights the importance of utilizing renewable energy sources to accelerate the transition to a sustainable energy future.

This study demonstrates the effectiveness of the K-Nearest Neighbor (KNN) algorithm in predicting CO2 emissions across various energy sources. The results indicate that fossil fuels remain the primary contributors to emissions in the model. Nonetheless, wind energy remains a significant energy source, even when fossil fuels are not available. Increased investments could significantly aid Egypt's efforts to reduce emissions and transition to cleaner energy sources, such as wind and solar energy.

Policymakers must implement strong regulatory frameworks and financial incentives to accelerate the transition to renewable energy. To reduce Egypt's carbon footprint, it is crucial to enhance the wind and solar energy infrastructure and make informed investments in energy efficiency and smart grids. To ensure a balanced and sustainable energy mix, future research should focus on the long-term sustainability of renewable energy growth by analyzing technological developments, conducting cost-benefit evaluations, and reviewing government incentives.

The paper emphasizes the significant impact of policy changes and technological advancements on Egypt's energy transition. Although renewable energy use is increasing, several structural challenges persist, including intermittency, storage constraints, and difficulties with grid integration. Research indicates that improving energy storage capabilities, modernizing grid infrastructure, and adopting hybrid energy systems can enhance the efficiency of renewable energy sources. Government-led programs, such as carbon pricing schemes and subsidies for green energy projects, can further accelerate the shift to sustainable energy. A cooperative strategy that combines private sector investments, international collaborations, and legislative actions is essential for achieving long-term energy security and environmental sustainability.

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