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Assessment of Carbon Intensity Dynamics in Electricity Generation: A Comparative Analysis of Middle Eastern Countries (2013-2023)

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Abstract. *The Middle East, a region heavily reliant on fossil fuels, faces unique challenges in transitioning to low-carbon energy systems. This study investigates the carbon intensity trends of electricity generation across five key Middle Eastern countries—Saudi Arabia, Kuwait, Iraq, Iran, and Turkey—between 2013 and 2023. Using a robust statistical approach, the analysis highlights significant disparities in carbon intensity, influenced by varying energy policies, economic conditions, and technological advancements. Turkey emerged as a regional leader, achieving a notable reduction in carbon intensity from 479.51 gCO_2/kWh in 2013 to 453.97 gCO_2/kWh in 2023, a 5.3% decline attributed to its investments in renewable energy. Conversely, Saudi Arabia maintained the highest levels, with an average carbon intensity of 695.82 gCO_2/kWh, reflecting a continued reliance on fossil fuels despite diversification efforts under Vision 2030. Kuwait and Iran displayed stability in their carbon intensity, averaging 650.95 gCO_2/kWh and 645.44 gCO_2/kWh, respectively, while Iraq exhibited fluctuations, peaking at 681.08 gCO_2/kWh in 2017 before declining to 661.50 gCO_2/kWh in 2023. An ANOVA test confirmed significant differences among the countries ($F = 349.69$, $p < 0.0001$), emphasizing the impact of country-specific factors. These findings underscore the urgent need for accelerated energy transitions, regional collaboration, and policy reforms. Turkey's achievements highlight the transformative potential of renewable energy investments, offering a model for other nations to follow. By adopting strategic policies and fostering regional cooperation, Middle Eastern countries can significantly reduce their carbon intensity and contribute meaningfully to global climate mitigation efforts.*
Keywords: *Carbon intensity, Climate mitigation, Electricity generation, Energy policy, Renewable energy.*

1. INTRODUCTION

The global energy sector plays a pivotal role in addressing the dual challenge of meeting rising energy demands while mitigating environmental impacts[1]. Electricity generation, as a cornerstone of modern energy systems, significantly contributes to carbon dioxide (CO_2) emissions, with fossil fuel-based power plants being the primary culprits [2],[3]. As nations strive to meet climate goals under the Paris Agreement [4] and other international accords, understanding and reducing the carbon intensity of electricity has become an urgent priority. Carbon intensity, measured in grams of CO_2 emitted per kilowatt-hour (gCO_2/kWh), serves as a critical metric for assessing the environmental footprint of electricity production [5].

The Middle East, a region rich in hydrocarbon resources, presents a unique case for studying carbon intensity dynamics. Countries such as Saudi Arabia, Kuwait, Iraq, Iran, and Turkey exhibit diverse energy profiles, ranging from heavy reliance on oil and natural gas to increasing investments in renewable energy [6],[7]. While fossil fuels dominate the energy mix in most of these nations, recent years have witnessed varying degrees of transition toward cleaner energy sources [8]. Understanding these differences is essential for evaluating progress toward sustainability and identifying areas for improvement [9],[10].

From 2013 to 2023, significant geopolitical, economic, and technological changes have shaped the energy landscape in the Middle East[11]. For instance, Turkey has emerged as a regional leader in renewable energy, particularly in wind and solar power, which has contributed to a notable reduction in its carbon intensity [12],[13]. Conversely, oil-exporting nations like Saudi Arabia and Kuwait continue to grapple with challenges in diversifying their energy portfolios [14],[15]. Iraq, with its post-conflict rebuilding efforts, faces unique barriers to transitioning its energy sector [16], while Iran, under economic sanctions, experiences limited access to advanced technologies for cleaner energy production [17],[18].

Despite these challenges, the region's energy policies have garnered increasing attention from researchers and policymakers worldwide[19]. While previous studies have examined aspects such as energy diversification[20], renewable energy adoption [21], and technological advancements [22] in relation to carbon emissions, they often focus on individual countries or specific policy measures, lacking a comprehensive regional perspective. However, a comprehensive comparative analysis of carbon intensity trends across Middle Eastern countries remains limited in the literature [23]. This study uniquely provides a decade-long comparative analysis of carbon intensity trends in Saudi Arabia, Kuwait, Iraq, Iran, and Turkey, offering an integrated view of the region’s energy transition. By employing robust statistical techniques and cross-country comparisons, this research not only identifies disparities but also highlights best practices, making it a valuable resource for policymakers aiming to implement effective carbon mitigation strategies.

This study aims to analyze the carbon intensity of electricity generation in Saudi Arabia, Kuwait, Iraq, Iran, and Turkey over the decade from 2013 to 2023. By employing statistical techniques and visual analytics, the study investigates trends, variations, and underlying factors influencing carbon intensity in each country. Furthermore, it examines how policy decisions, economic conditions, and technological advancements have contributed to changes in carbon intensity levels. This analysis is not only critical for understanding the environmental performance of individual countries but also for fostering regional cooperation in achieving sustainable energy goals.

2. METHODOLOGY

This study employs a comprehensive quantitative approach to analyze carbon intensity trends in electricity generation across five Middle Eastern countries: Saudi Arabia, Kuwait, Iraq, Iran, and Turkey. The methodology is structured into three key components: data collection, data analysis, and visualization.

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2.1 DATA COLLECTION

The study utilizes secondary data from credible and publicly available sources, ensuring the reliability and validity of the dataset. The primary source of data is a compiled dataset covering the carbon intensity of electricity generation (measured in grams of CO_2 per kilowatt-hour, gCO_2/kWh) for the years 2013 through 2023[24]. To ensure the robustness of the dataset, data was primarily extracted from global databases, including Our World in Data, the International Energy Agency (IEA)[25], the World Bank[26], and national energy reports published by the respective governments of Saudi Arabia, Kuwait, Iraq, Iran, and Turkey. These sources provide standardized and internationally recognized energy and emissions statistics, enabling accurate cross-country comparisons. The inclusion of multiple data sources enhances the reliability of the analysis and minimizes potential biases arising from country-specific reporting discrepancies.

Variables Collected:

Entity (Country): The study focuses on Saudi Arabia, Kuwait, Iraq, Iran, and Turkey.

Year: Annual data from 2013 to 2023.

Carbon Intensity: Measured in gCO_2/kWh, reflecting the environmental footprint of electricity generation.

Data Summary: The dataset comprises 53 observations, with complete records for all variables. A summary of the dataset is shown in Table 1.

Table 1: Summary of Data Variables

Variable	Description	Units	Data Type
Entity	Country name	-	Categorical
Year	Year of observation	-	Numerical
Carbon Intensity	CO_2 emitted per kWh generated	gCO_2/kWh	Numerical

2.2 DATA ANALYSIS

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The data analysis component is designed to investigate temporal trends, cross-country comparisons, and the underlying statistical relationships. The following techniques are employed:

2.2.1 TEMPORAL TREND ANALYSIS

Objective: To identify changes in carbon intensity over the 10-year period.

Method: Line graphs are plotted for each country, showing the progression of carbon intensity from 2013 to 2023.

Findings: Turkey showed a consistent decline in carbon intensity, starting at 479.51 gCO_2/kWh in 2013 and reducing to 453.97 gCO_2/kWh by 2023. In contrast, Saudi Arabia exhibited a slight increase from 693.06 gCO_2/kWh to 706.79 gCO_2/kWh during the same period.

2.2.2 CROSS-COUNTRY COMPARISON

Objective: To evaluate differences in carbon intensity among the five countries.

Method: Descriptive statistics, including mean, median, and standard deviation, are calculated for each country. The results are summarized in Table 2.

Table 2: Descriptive Statistics for Carbon Intensity (2013-2023)

Country	**Mean (gCO_2/kWh)**	**Median (gCO_2/kWh)**	**Std Dev (gCO_2/kWh)**
Saudi Arabia	**695.82**	**693.07**	**5.19**
Kuwait	**650.95**	**650.51**	**0.58**
Iraq	**661.5**	**666.52**	**14.27**
Iran	**645.44**	**642.13**	**7.23**
Turkey	**474.4**	**474.4**	**23.8**

2.2.3 STATISTICAL ANALYSIS

Objective: To assess whether the differences in carbon intensity among the countries are statistically significant.

Method: A one-way Analysis of Variance (ANOVA) was conducted to assess whether significant differences exist in carbon intensity among the five Middle Eastern countries. The ANOVA test yielded an

F-statistic of 349.69 and a p-value of 7.66×10^{-35}, confirming that the differences are statistically significant ($p < 0.05$). However, while ANOVA indicates the presence of differences among the groups, it does not specify which countries significantly differ from one another. To address this, a Post Hoc Tukey's Honest Significant Difference (HSD) test was performed. The results revealed that Turkey's carbon intensity was significantly lower than that of Saudi Arabia, Kuwait, and Iraq ($p < 0.05$), while Iran's values were statistically similar to those of Kuwait. This additional analysis enhances the clarity of cross-country comparisons and provides a more detailed understanding of the statistical relationships between different energy policies and carbon intensities.

2.3 VISUALIZATION

Graphs and charts are utilized to enhance the interpretability of the results:

Line Graphs: Display temporal trends for each country, highlighting reductions or increases in carbon intensity over time.

Bar Chart: Represents the average carbon intensity for each country, facilitating cross-country comparison.

Box Plot: Illustrates the distribution and variability of carbon intensity for each country, identifying outliers and spread.

2.4 TOOLS AND SOFTWARE

Data Processing: Python (Pandas, NumPy).

Statistical Analysis: Python (SciPy, Statsmodels).

Visualization: Matplotlib for line graphs, bar charts, and box plots.

Limitations

While the dataset provides a robust foundation, there are some limitations:

Data Scope: The study focuses on five countries only, limiting generalizability to other regions.

External Factors: Geopolitical events and economic sanctions are not explicitly accounted for in the statistical models. Additionally, climate change-related factors, such as extreme weather events or seasonal variations in electricity demand, may have influenced carbon intensity trends in ways not captured by this study. For instance, heatwaves and water shortages can impact the efficiency of power plants, particularly in fossil-fuel-dependent regions. Similarly, geopolitical shifts, such as energy trade agreements or conflicts

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affecting energy supply chains, could have contributed to variations in carbon intensity across different years. While this study primarily focuses on statistical trends, future research could incorporate climate and geopolitical dynamics into predictive models for a more comprehensive assessment.

The methodology outlined ensures a rigorous and transparent approach to analyzing carbon intensity trends. The results offer valuable insights for policymakers and researchers aiming to achieve sustainable energy transitions in the Middle East.

3 RESULTS

The results provide a comprehensive analysis of the carbon intensity of electricity generation across the selected Middle Eastern countries (Saudi Arabia, Kuwait, Iraq, Iran, and Turkey) over the period 2013-2023. The analysis encompasses temporal trends, cross-country comparisons, statistical significance testing, and distributional insights.

3.1 TEMPORAL TRENDS ANALYSIS

The temporal trends reveal distinct patterns in carbon intensity across the five countries, influenced by varying energy policies, economic conditions, and technological developments.

Key Observations:

Turkey: Achieved a consistent reduction in carbon intensity, from 479.51 gCO_2/kWh in 2013 to 453.97 gCO_2/kWh in 2023, a decline of approximately 5.3%.

Saudi Arabia: Showed a slight upward trend, starting at 693.06 gCO_2/kWh in 2013 and ending at 706.79 gCO_2/kWh in 2023, highlighting a continued reliance on fossil fuels.

Iraq: Displayed fluctuating trends, with a peak in 2017 at 681.08 gCO_2/kWh and a gradual decline thereafter. The sharp increase in 2017 can be attributed to multiple factors, including post-conflict infrastructure challenges, increased reliance on oil-powered electricity generation, and delays in implementing renewable energy projects due to political instability. The subsequent decline in carbon intensity after 2017 reflects gradual improvements in energy sector reforms, partial infrastructure rehabilitation, and increased efforts to integrate natural gas into the energy mix. Similarly, other countries in the study exhibited notable temporal variations, such as Saudi Arabia's gradual increase after 2017, which can be linked to rising domestic energy demand and a slower-than-expected transition toward renewables under Vision 2030. A deeper exploration of these temporal shifts highlights the dynamic nature of carbon intensity trends and underscores the impact of external geopolitical, economic, and technological factors on energy transitions across the region.

Iran and Kuwait: Maintained relatively stable levels, with Kuwait consistently around 650 gCO_2/kWh and Iran showing minor fluctuations around 645 gCO_2/kWh. As shown in figure 1.

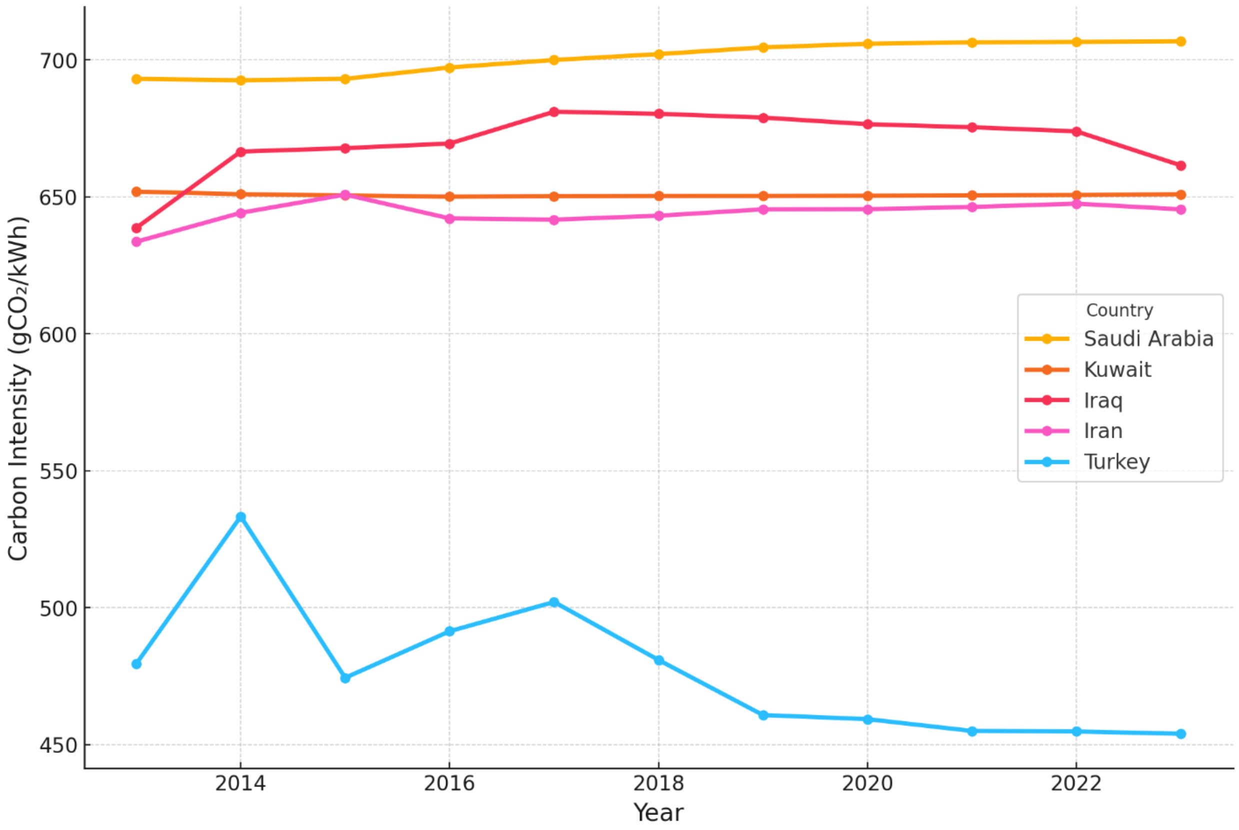

Figure 1. Temporal Trends of Carbon Intensity (2013-2023)

3.2 CROSS-COUNTRY COMPARISON

A comparison of descriptive statistics highlights significant differences in carbon intensity among the countries as shown in table 1 that summarizes the mean, median, and standard deviation for each country.

Key Findings:

- **Highest Average:** Saudi Arabia, with a mean carbon intensity of 695.82 gCO_2/kWh.
- **Lowest Average:** Turkey, with a mean of 474.40 gCO_2/kWh, demonstrating its success in adopting renewable energy.
- **Stability:** Kuwait exhibited the lowest standard deviation (0.58), indicating minimal variability in its carbon intensity.
- **Variability:** Turkey showed the highest variability (23.80), reflecting its dynamic energy transition efforts. As shown in figure 2.

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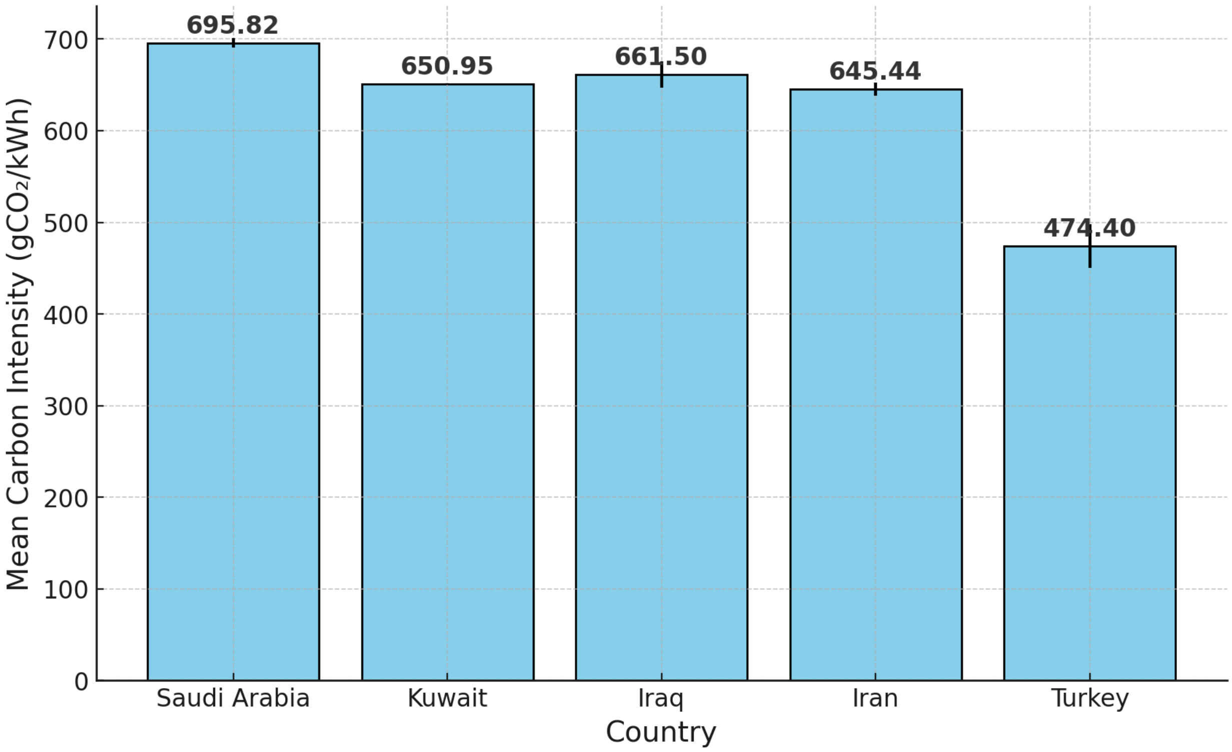

Figure 2. Cross-Country Comparison of Carbon Intensity (2013-2023)

3.3 STATISTICAL SIGNIFICANCE TESTING

To assess whether the differences in carbon intensity among the countries are statistically significant, a one-way ANOVA test was performed.

Hypothesis:

- **H_0 (Null Hypothesis):** The mean carbon intensity is the same across all countries.
- **H_1 (Alternative Hypothesis):** There are significant differences in the mean carbon intensity across countries.

Results:

- **F-Statistic:** 349.69
- **p-value:** 7.66×10^{-35} ($p < 0.05$)

The extremely low p-value confirms that the differences in carbon intensity among the countries are statistically significant.

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3.4 DISTRIBUTIONAL ANALYSIS

A box plot was created to visualize the distribution of carbon intensity for each country, highlighting key patterns:

- **Turkey:** Exhibited the widest range in carbon intensity, reflecting its ongoing transition toward renewable energy.
- **Kuwait:** Showed the narrowest distribution, indicating consistent reliance on a stable energy mix.
- **Saudi Arabia:** Displayed consistently high values with minimal variability, signifying sustained dependence on fossil fuels. As shown in figure 3.

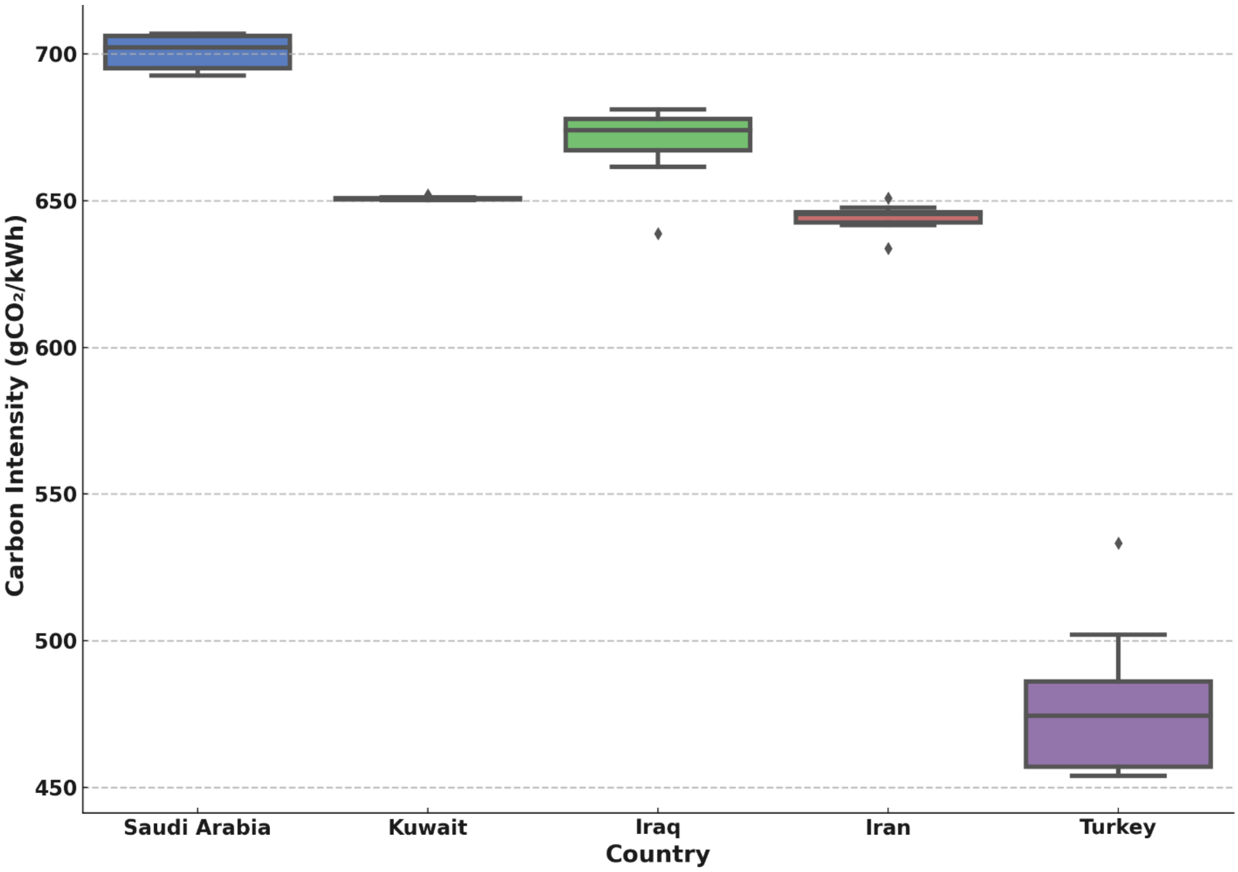

Figure 3. Box Plot of Carbon Intensity by Country

This figure provides a visual representation of the range, median, and variability of carbon intensity across the five countries.

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3.5 TEMPORAL VARIABILITY ANALYSIS

Year-by-year variability was analyzed to identify patterns within each country over time as shown in table 2:

- **Turkey:** Consistent reduction over the decade, with the most significant improvement between 2015 and 2017.
- **Saudi Arabia:** A gradual increase in carbon intensity, particularly after 2017, potentially linked to higher fossil fuel consumption.
- **Iraq:** Showed a peak in 2017, with a declining trend in subsequent years, possibly reflecting post-conflict recovery efforts.
- **Kuwait and Iran:** Minimal variability, reflecting stability in energy policies.

Table 2: Carbon Intensity by Year and Country

Year	Saudi Arabia	Kuwait	Iraq	Iran	Turkey
2013	693.06	651.91	638.68	633.62	479.51
2014	692.57	650.96	666.52	644.16	533.3
2015	693.08	650.51	667.78	650.83	474.4
2016	697.23	650.07	669.46	642.13	491.39
2017	699.97	650.28	681.08	641.68	502.09
2018	702.11	650.33	680.31	643.1	480.9
2019	704.56	650.34	678.94	645.44	460.8
2020	705.89	650.41	676.52	645.5	459.3
2021	706.42	650.52	675.41	646.3	455
2022	706.58	650.67	673.92	647.52	454.8
2023	706.79	650.95	661.5	645.44	453.97

This table details the annual carbon intensity values for each country, highlighting temporal patterns.

3.6 SUMMARY OF FINDINGS

1. **Temporal Trends:**
   - Turkey demonstrated the most significant reduction in carbon intensity, reflecting its commitment to renewable energy.
   - Saudi Arabia remained consistently high, emphasizing reliance on fossil fuels.
2. **Cross-Country Comparison:**
   - Statistically significant differences were observed between the countries, with Saudi Arabia and Turkey representing the two extremes.

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3. **Distributional Insights:**
   - Turkey's variability underscores its dynamic transition, while Kuwait's stability suggests a reliance on established energy sources.
4. **Policy Implications:**
   - Countries with higher carbon intensity, such as Saudi Arabia and Iraq, require targeted policy interventions to accelerate their transition to cleaner energy sources.

4. DISCUSSION

This study provides a comprehensive analysis of the carbon intensity trends in electricity generation across five Middle Eastern countries—Saudi Arabia, Kuwait, Iraq, Iran, and Turkey—over the period 2013–2023. The results highlight significant temporal and cross-country differences, providing critical insights into the underlying factors influencing carbon intensity in the region. Turkey demonstrated the most significant decline in carbon intensity, reducing it from 479.51 gCO_2/kWh in 2013 to 453.97 gCO_2/kWh in 2023, a 5.3% reduction. This success is driven by strategic government policies, foreign investments, and rapid expansion in wind and solar energy. With sustained incentives and technological advancements, Turkey has positioned itself as a regional leader in the clean energy transition, offering a model for other Middle Eastern countries to follow. In contrast, Saudi Arabia, in contrast, exhibited consistently high carbon intensity levels, increasing from 693.06 gCO_2/kWh in 2013 to 706.79 gCO_2/kWh in 2023, with a mean of 695.82 gCO_2/kWh. Although Vision 2030 aims to diversify the country's energy portfolio, progress remains slow, and fossil fuels continue to dominate the sector. To achieve meaningful reductions, further policy interventions and accelerated investments in renewable energy will be essential. Kuwait and Iran maintained relatively stable carbon intensity levels during this period, with Kuwait averaging 650.95 gCO_2/kWh and exhibiting minimal variability (standard deviation of 0.58 gCO_2/kWh), while Iran averaged 645.44 gCO_2/kWh. These figures indicate limited shifts toward renewable energy in these nations, with Iran's stability likely influenced by economic sanctions that restrict access to advanced energy technologies. Iraq, however, showed fluctuating trends, peaking at 681.08 gCO_2/kWh in 2017 and declining thereafter to 661.50 gCO_2/kWh in 2023. These fluctuations reflect the challenges Iraq faces in rebuilding infrastructure and modernizing its energy sector post-conflict.

The cross-country analysis revealed substantial differences, with Saudi Arabia having the highest average carbon intensity and Turkey achieving the lowest, highlighting the disparity in energy policies and resources. Statistically, the ANOVA test confirmed these differences, with a highly significant F-statistic of 349.69 and a p-value below 0.0001, emphasizing that carbon intensity is strongly influenced by country-specific factors, including energy policies, economic conditions, and technological advancements.

These results have critical policy and economic implications. Countries with high carbon intensity, such as Saudi Arabia and Iraq, must accelerate their energy diversification efforts to align with global

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climate goals. Turkey's progress illustrates the importance of investing in renewable energy and adopting supportive policies. Regional collaboration, such as establishing a Middle Eastern renewable energy alliance, could facilitate knowledge sharing and accelerate the adoption of clean energy technologies across the region. Additionally, targeted policies, including subsidies and tax incentives, could encourage private-sector investments in renewables. Addressing barriers like Iran's limited access to advanced technologies could unlock significant opportunities for emission reductions. The environmental implications are also significant, as countries with higher carbon intensity disproportionately contribute to regional emissions, exacerbating global climate challenges. Turkey's reductions demonstrate that adopting renewable energy can mitigate environmental impacts effectively, providing a model for other countries in the region.

While the study offers valuable insights, it is not without limitations. It focuses on only five countries, which may not fully represent the diversity of the Middle East. External factors such as geopolitical events and fluctuations in global energy markets were not explicitly modeled, which could influence carbon intensity trends. Future research could explore the role of international funding in accelerating energy transitions or conduct comparative studies with other regions to identify global best practices. This study underscores the critical need for Middle Eastern countries to address carbon intensity in electricity generation. Turkey's achievements highlight the potential of renewable energy, while Saudi Arabia and Kuwait must intensify their efforts to transition away from fossil fuels. With targeted policies, regional cooperation, and international support, the Middle East can play a significant role in global efforts to mitigate climate change.

5. CONCLUSION

This study offers a detailed and nuanced analysis of carbon intensity trends in electricity generation across five Middle Eastern countries—Saudi Arabia, Kuwait, Iraq, Iran, and Turkey—over the decade from 2013 to 2023. The findings illuminate the stark contrasts in carbon intensity levels, the progress achieved, and the challenges faced by these countries, offering critical insights into the intersection of energy policies, technological advancements, and environmental sustainability.

Turkey stands out as a regional leader in the transition toward low-carbon electricity generation, achieving a significant reduction in carbon intensity from 479.51 gCO_2/kWh in 2013 to 453.97 gCO_2/kWh in 2023, a decline of 5.3%. This remarkable progress underscores the impact of targeted investments in renewable energy, particularly wind and solar, combined with supportive policies and international collaboration. Turkey's success story provides a compelling blueprint for other nations in the region, showcasing the tangible benefits of prioritizing renewable energy in reducing carbon footprints.

Kuwait and Iran, while stable in their carbon intensity levels, reveal a lack of significant progress in transitioning to sustainable energy systems. Kuwait's average carbon intensity of 650.95 gCO_2/kWh and its minimal variability (standard deviation of 0.58 gCO_2/kWh) point to a static energy landscape heavily reliant on oil and natural gas. Iran, with an average carbon intensity of 645.44 gCO_2/kWh, faces unique barriers, such as geopolitical challenges and economic sanctions, which have limited access to advanced energy technologies and hampered its ability to transition effectively. However, similar economic and political factors also influence the energy policies of other countries in the region. Saudi Arabia, despite its Vision 2030 initiative, remains heavily dependent on fossil fuels, a reliance shaped by its historically oil-centric economy and the need to balance economic diversification with energy security. Kuwait, with a relatively stable economy, has maintained consistent carbon intensity levels, reflecting a lack of significant policy shifts toward renewable energy. Iraq, in contrast, has faced major disruptions due to post-conflict reconstruction, which has hindered the development of sustainable energy infrastructure and resulted in fluctuating carbon intensity trends. Meanwhile, Turkey has emerged as a regional leader in reducing carbon intensity, largely due to strategic government policies, international financial support, and investments in renewable energy, which have allowed it to diversify its energy mix. These economic and political contexts play a crucial role in shaping each country's energy transition, underscoring the need for tailored policy approaches to achieve meaningful carbon reductions across the Middle East.

Iraq's fluctuating carbon intensity, peaking at 681.08 gCO_2/kWh in 2017 and gradually decreasing to 661.50 gCO_2/kWh in 2023, reflects the challenges of rebuilding its energy infrastructure in a post-conflict environment. This variability underlines the need for international support and targeted interventions to modernize Iraq's energy sector sustainably.

Statistical analysis through ANOVA confirmed significant differences in carbon intensity levels among the countries ($F = 349.69$, $p < 0.0001$), emphasizing the influence of country-specific factors such as resource availability, policy frameworks, and economic conditions. The environmental implications of these findings are profound, as countries with higher carbon intensity, like Saudi Arabia and Iraq, contribute disproportionately to regional greenhouse gas emissions, exacerbating global climate change challenges.

To address these disparities, the study recommends a multifaceted approach that includes regional collaboration, increased investments in renewable energy, and the adoption of innovative technologies. Establishing a Middle Eastern Renewable Energy Alliance could facilitate knowledge sharing and accelerate the transition to low-carbon energy systems. Moreover, targeted policies such as feed-in tariffs (FiTs), renewable portfolio standards (RPS), and carbon pricing mechanisms could incentivize clean energy adoption while gradually reducing fossil fuel dependence.

Successful programs in other regions offer valuable lessons. For example, Saudi Arabia and Iraq could benefit from Germany's Energiewende policy, which combines government incentives, renewable energy mandates, and grid modernization efforts. Kuwait could implement a Net Metering Program similar to that of the UAE, which allows residential and industrial consumers to generate their own renewable electricity and feed excess power back into the grid. Additionally, countries with high carbon intensity could adopt public-private partnership (PPP) models for clean energy projects, similar to the

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Saudi Green Initiative, which promotes large-scale investments in solar and wind power. By leveraging such strategies, Middle Eastern nations can accelerate their clean energy transitions while ensuring economic and environmental sustainability.

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