Assessing Renewable Energy's Impact on Environmental Health and Pollutant Concentrations in the U.S. within North American region

1. Introduction

The significance of renewable energy adoption lies in its potential to enhance environmental health amidst global efforts to mitigate climate change. This report examines the United States as a focal region, leveraging its wealth of high-quality datasets, diverse ecological conditions, and prominent air quality concerns.

The study investigates the question: "Does increased renewable energy consumption lead to measurable improvements in environmental health and pollutant concentrations?" By analyzing the interaction between renewable energy usage, air quality, and emissions data, this report seeks to provide academically grounded insights to inform sustainable energy policies and practices.

2. Data Utilized

2.1 ETL Pipeline Process

A robust Extract-Transform-Load (ETL) pipeline was developed to process raw data into a consistent and analyzable format. Temporal standardization ensured all data adhered to uniform time-series structures (monthly or yearly). Missing values were systematically addressed using forward and backward filling techniques. Emissions data were restructured into long format for compatibility, and the final datasets were stored in an SQLite database containing three tables *emissions*, *pollution*, and *renewable energy*.

2.2 Renewable Energy Consumption Table

This table encompasses monthly records from January 1973 to January 2024, documenting energy consumption across sources such as Hydroelectric, Solar, Wind, and Biomass. The data is segmented by Commercial, Residential, and Industrial sectors, and values are reported in trillion British Thermal Units (BTU). The source of this dataset is the Kaggle, licensed under U.S. Government Work.

2.3 Pollution Table

Spanning from 2000 to 2023, this table includes daily Air Quality Index (AQI) measurements for key pollutants such as Nitrogen Dioxide (NO_2), Sulfur Dioxide (SO_2), Carbon Monoxide (CO), and Ozone (O_3). AQI values adhere to standards set by the U.S. Environmental Protection Agency (EPA) to reflect health risks. This dataset is governed by the U.S. Government Work.

2.4 Emissions Table

This table provides annual records from 1990 to 2023, detailing pollutant emissions by type and source, including industrial activities, transportation, and fuel combustion. The source is the U.S. Environmental Protection Agency (EPA), and usage complies with the EPA Data License.

2.5 Data License Compliance

The data utilized in this analysis comply with all licensing requirements. Permissions for non-commercial use were strictly adhered to, and appropriate attribution was provided to all data sources. The licensing terms of each dataset were meticulously observed to ensure ethical and lawful use in this academic investigation.

3. Analysis

The analysis process employed a variety of methodologies to evaluate the relationship between renewable energy adoption and environmental health. The analysis utilized key Python libraries. Pandas handled data manipulation, Matplotlib and Seaborn generated visualizations, and SciPy supported advanced statistical analysis.

The Renewable Energy Consumption dataset provided critical insights into energy consumption trends across sectors and sources. Long-term trends revealed a steady rise in renewable energy usage, particularly after 2000 (Figure 1(a)). Sectoral analysis revealed the dominance of the Electric Power sector, followed by Industrial and Transportation sectors (Figure 1(b)). Source-wise, Wood Energy and Biomass have been major contributors historically, but Wind and Solar energy have grown significantly in recent decades, indicating a shift toward sustainable sources (Figure 1(d)). Seasonal patterns highlighted variations, with energy consumption peaking in summer and dropping in winter (Figure 1(e)).

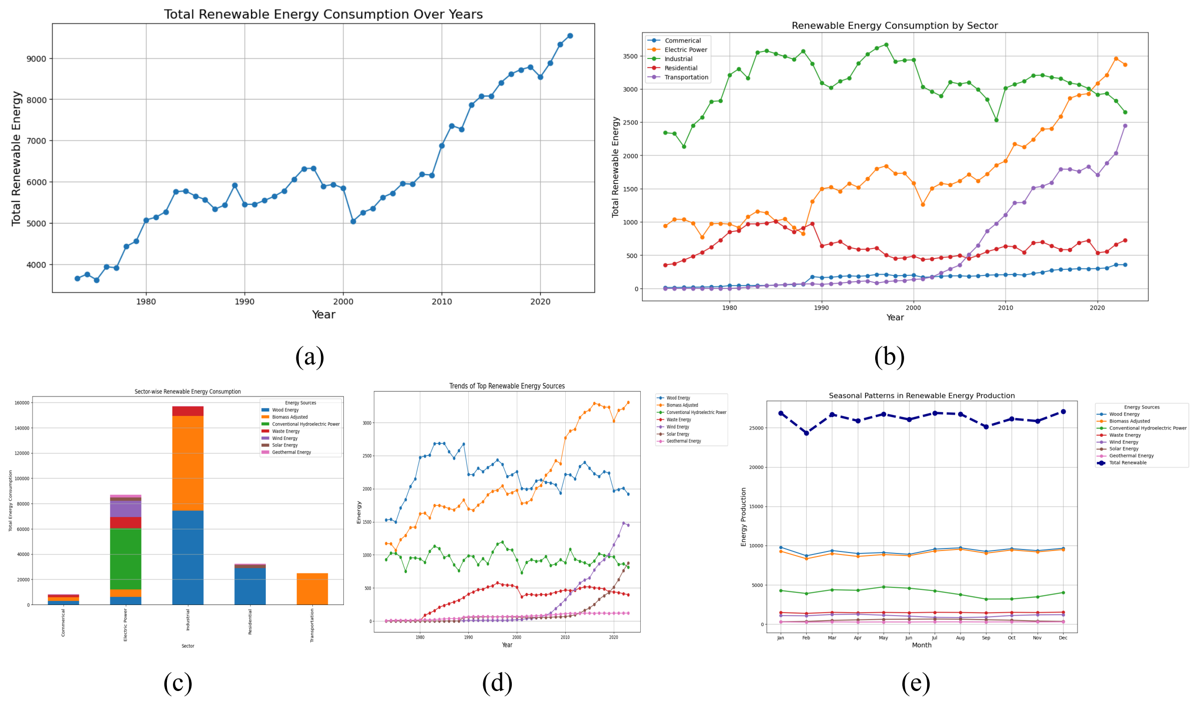
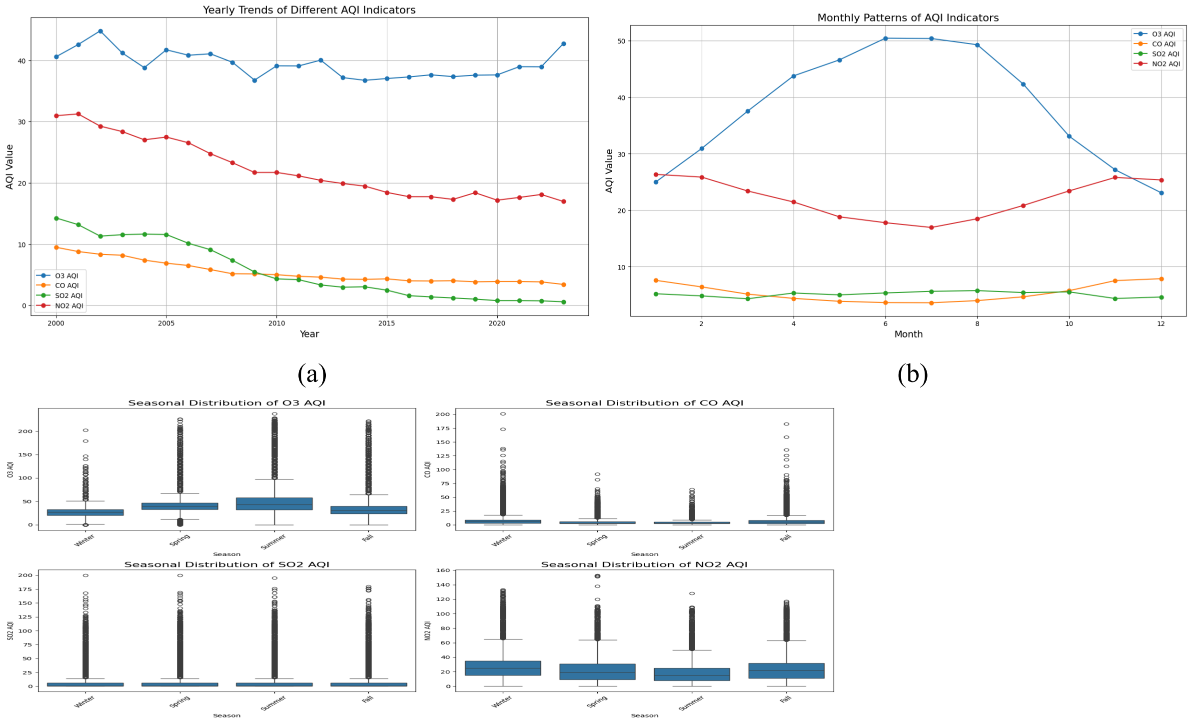


Figure 1: Renewable energy consumption insights.

The Air Quality Index (AQI) dataset provided further insights into pollutant trends over time. Yearly trends demonstrated declines in O3, NO2, SO2, and CO AQI values, reflecting effective emission control measures (Figure 2(a)). Seasonal analysis of AQI metrics revealed distinct patterns; for instance, Ozone levels peaked in summer due to photochemical reactions, while NO2 and SO2 levels were higher in winter, linked to heating and industrial activities (Figure 2(b), 2(c)).

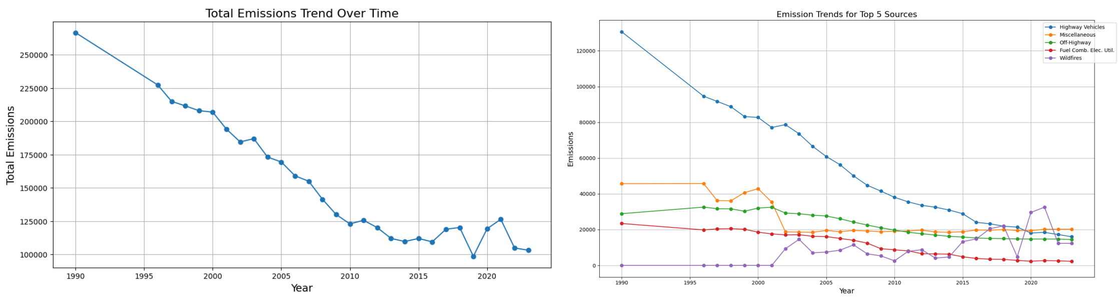


(a) (b)

(c)

Figure 2: AQI trends and seasonal distribution

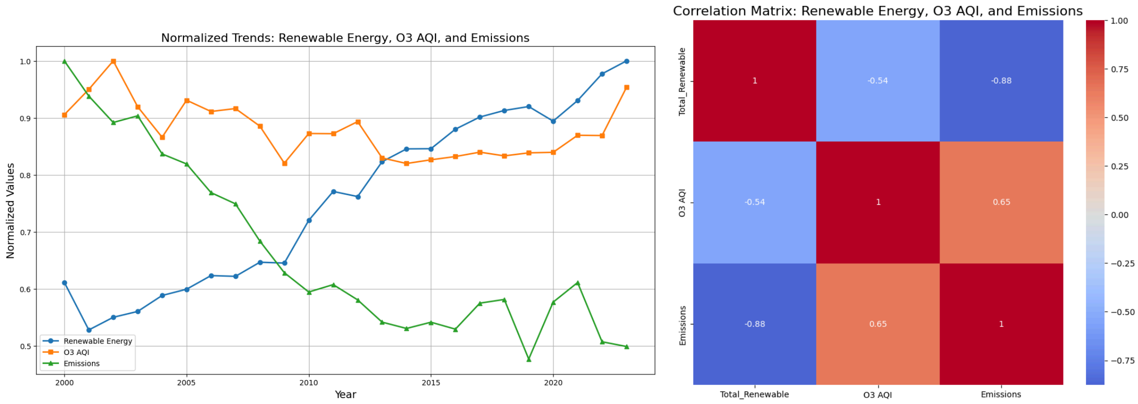
The Emissions dataset shed light on pollutant source trends and total emission. A significant decline in total emissions was observed from 1990 to 2023, attributed to advancements in emission control technologies and stricter environmental regulations (Figure 3(a)). Trends of top emission sources (Figure 3(b)) highlighted a significant reduction in highway vehicle emissions over time, while contributions from other sources showed less pronounced changes..



(a) (b)

Figure 3: Total emission trend and emission trends for top 5 sources.

The combined analysis of renewable energy, AQI, and emissions data highlights the interconnected dynamics between energy consumption, air quality, and pollutant reduction. Normalized trends (Figure 4(a)) show a clear inverse relationship: as renewable energy usage increased, emissions significantly decreased, reflecting the effectiveness of renewable energy adoption in curbing pollution. Ozone AQI displayed a positive decline, signifying improved atmospheric conditions and the impact of reduced emissions on air quality. The correlation matrix plot (Figure 4(b)) and scatter plots with regression line (Figure 4(c)) further reinforced these relationships. A strong negative correlation (-0.88) was observed between renewable energy consumption and emissions, while a moderate negative correlation (-0.54) was evident between renewable energy and O3 AQI. These results validate the hypothesis that renewable energy adoption mitigates environmental pollution and improves air quality. Year-over-year changes (Figure 4(d)) highlighted consistent growth in renewable energy alongside declining emissions and O3 AQI, further proving the positive impact of clean energy transitions.



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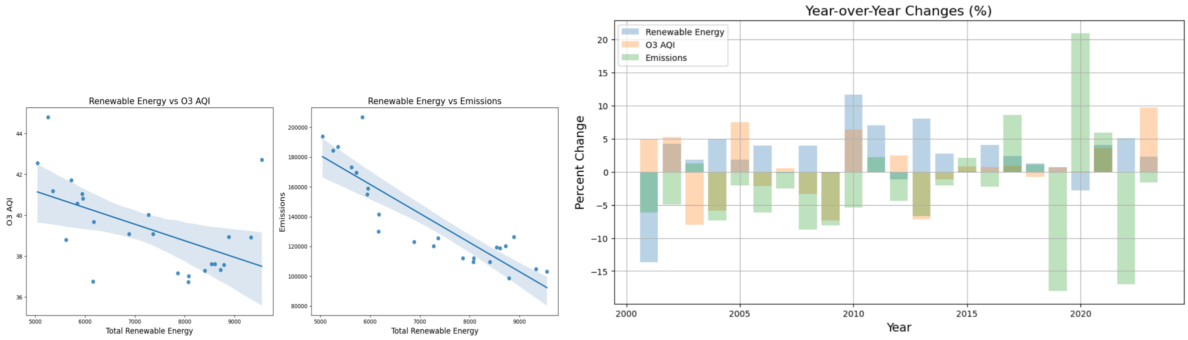

(c) (d)

Figure 4: Correlation insights among renewable energy consumption, O3 AQI and emissions.

4. Conclusion

This analysis demonstrates that increased renewable energy consumption leads to significant improvements in environmental health and pollutant concentrations. The integration of renewable energy, AQI, and emissions data highlights the benefits of clean energy transitions across various sectors, demonstrating how declining emissions align with rising renewable energy usage. While the analysis addresses the question effectively, some limitations remain. The study primarily relies on aggregated data, which may mask local variations and specific regional impacts. The temporal resolution of the data for analytics, being primarily annual or monthly, might not capture short-term fluctuations or immediate cause-and-effect relationships. Additionally, the analysis does not account for external factors such as economic conditions, policy changes, or technological advancements that could influence these relationships. Weather patterns and seasonal variations, which can significantly impact both renewable energy production and air quality, were not accounted for in this analysis. Despite these limitations, the findings confirm renewable energy's vital role in environmental sustainability, offering valuable insights for policymakers and stakeholders committed to combating climate change and enhancing air quality.