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Energy Use and CO_2 Emissions in Guangdong's Manufacturing Hub: An econometric and Deep learning approach

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Abstract

China's most populous and economically dynamic province (Guangdong), is facing challenges in balancing rapid industrialization with sustainable energy use. As a major contributor to CO_2 emissions, the province's energy consumption patterns reflect its reliance on fossil fuels. The paper investigates the impact of fossil fuel energy consumption, particularly the interconnection between coal, petroleum and CO2 emissions, consequently, the paper forecast CO2 emissions trend in Guangdong province. The paper employs econometric technique (Vector Autoregression_VAR model) and deep learning approach (Long Short-Term Memory_LSTM model) covering a dataset between 1999-2021. The results based on VAR technique suggest that Coal and petroleum significantly impact CO2 emission, subsequently degrades environment. The forecasting results based on LSTM model suggest increasing CO2 emission trend until 2025, however, the trend declines in the following years. The LSTM-based forecasting results indicate that CO_2 emissions in Guangdong will continue rising until 2025, followed by a steady decline in subsequent years. These findings suggest that alternative energy sources such as wind and solar are reliable and friendly energy sources in achieving sustainable energy targets.

Keywords: *Energy consumption, coal, petroleum, Co2 emissions.*

1. Introduction

Guangdong Province has demonstrated continuous industrial growth over the past decades. However, rapid industrial expansion in Guangdong has incurred considerable environmental costs due to the usage of contaminated energy fuels (Tian & Yang, 2016). This greenhouse gas increases with the level of CO_2 emissions is the primary component driving climate change while worsening the quality of air and posing high risks to human health of the local population (Guo et al., 2022; Qin et al., 2021; Yu et al., 2022; Zhou et al., 2017). The province continues to depend on traditional sources of energy such as coal and petroleum especially for industrial production and transport besides electricity hence

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leading to increased emission of greenhouse gases. Understanding fossil fuel consumption and the resulting CO_2 emissions enables the formulation of sustainable energy strategies crucial for reducing environmental harm (Balsalobre-Lorente et al., 2022; Karaaslan & Çamkaya, 2022; Liu et al., 2020).

The economic success of Guangdong and its major cities, Guangzhou and Shenzhen is relied heavily on coal and petroleum as its key fuel sources. Industrial activities and energy supply depend on coal, which forms the foundation of electricity generation and heavy manufacturing, while petroleum fuels meet transportation demands. Although these energy sources drive economic progress, they come at a cost—their CO_2 emissions harm the environment, contributing to global warming and damaging local ecosystems. Research needs to focus on studying how much CO_2 Guangdong releases through coal and petroleum usage because these sources show clear trade-offs.

In this study, the Vector Autoregression (VAR) model is used to analyse both direct and indirect effects of coal and petroleum consumption on CO_2 emissions. An ideal framework to analyze simultaneous and lagged interactions of the studied variables is the VAR approach. The research studies the effect of fuel consumption by treating the impact of coal and petroleum consumption on CO_2 emission.

This study provides detailed analysis for policymakers, environmental planners, and stakeholders seeking to balance economic growth with environmental protection in Guangdong. A systematic understanding of how CO_2 emissions relate to coal and petroleum consumption facilitates practical interventions, including reducing reliance on carbon-intensive energy sources, promoting cleaner alternatives, and aligning with global climate agreements (Rezaei Sadr et al., 2022; SWANBOROUGH, 2016). The research contributes to scholarly discourse in energy-environment studies, offering insights that could help other emerging economies address similar ecological concerns.

The investigation tackles the crucial issue of carbon emissions in Guangdong Province by employing sophisticated econometric techniques. By examining the connections between fossil fuel consumption and CO_2 output, we formulate data-driven policy suggestions for establishing sustainable, low-carbon energy frameworks.

2. Literature Review

Extensive research debates on the relationship between fossil fuel consumption and carbon dioxide (CO_2) emissions (Çıtak et al., 2021; Karaaslan & Çamkaya, 2022; Lei et al., 2022; Li, 2020; Liu et al., 2020; Rezaei Sadr et al., 2022), highlighting global climate and economic processes. As primary energy sources for industrial operations and transportation networks, fossils fuels such as, coal and petroleum significantly contribute to environmental pollutions. Comprehensive data provides robust evidence of environmental impacts, which scholars have extensively analyzed in rapidly developing Guangdong Province.

According to IEA (2022), coal combustion accounts for 40% of energy-related CO_2 emissions, positioning it as a critical target for reaching sustainable development (IEA, 2020). Studies focusing on China the world's leading coal consumer have confirmed a direct correlation between fossils fuels and increasing CO_2 levels (Ahmed et al., 2022). Although Guangdong has expanded investments in renewable energy, coal continues to dominate electricity generation and power energy-intensive industries like steel and iron production. Historical analyses identify industrial coal use as a key pollution source, underscoring the urgency for policies that accelerate clean energy adoption.

Petroleum-based fuels, including gasoline and diesel, constitute major greenhouse gases and emission source, particularly for transportation. According to Yang et al. (2024) Guangdong's petroleum demand has surged due to its role as a major hub in the international trade, coupled with growing port activities and vehicle numbers. Recent research by Wang et al. (2023) revealed transportation emissions consistently rise with economic expansion, highlighting the need for rapid deployment of renewable energy solutions. Econometric studies conducted by Pal and Sen (2023) show that minimizing petroleum usage leads to clean environment, especially in urban and industrial areas.

Scholars typically employ different econometric approaches to analyze fossil fuel and environmental degradation using time-series analysis, panel data models. (Kang et al., 2019) applied VAR modeling to examine dynamic interactions between coal consumption, GDP, and CO_2 emissions, identified short-term and long-term patterns. Daly et al. (2024); Meo and Adebayo (2024); Zuhal and Göcen (2024) used Granger causality tests to check bidirectional relationships between energy consumption and CO2 emissions. These advanced methodologies provide new analytical tools for investigating energy-emission dynamics.

Current literature proposes multiple strategies to reduce contaminated fuel dependence, including clean energy integration, improved energy efficiency. Yang et al. (2024) assessed the potential for renewable power in Guangdong, concluding solar and wind engry could substantially displace coal-fired generation. Ye et al. (2024) emphasized fuel efficiency standards and public transportation improvements as particularly effective measures for reducing petroleum-related emissions. However, few studies have applied advanced econometric techniques to Guangdong's unique context of rapid industrialization, high population density, and extensive trade activities, especially CO2 emissions trend.

This paper addresses these research gaps by implementing a VAR framework to explore coal and petroleum consumption impacts on CO_2 emissions in Guangdong and further highlights CO2 emissions trend. The methodology combines econometric techniques with deep learning model. The findings will contribute to academic discourse while supporting practical energy transition strategies for sustainable economic and social development, Guangdong and its major hub-cities.

3. Methodology

This study employs a Vector Autoregression (VAR) model to assess the relationships between coal consumption, petroleum consumption, and CO_2 emissions in Guangdong Province. The VAR framework is particularly suitable as it allows for the simultaneous evaluation of time-series variables and their dynamic interdependencies. The analysis relies on data from authoritative sources to ensure consistency and reliability. CO_2 emissions data were sourced from Guangdong's Environmental Statistical Yearbooks and the China Emission Accounts and Datasets. Coal and petroleum consumption figures, measured in tons of standard

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coal equivalent. The study covers the period from 1997 to 2021, natural logarithmic transformations were applied to stabilize variances and facilitate elasticity interpretations.

In the VAR model, CO_2 emissions acts as the dependent variable, while coal and petroleum consumption act as independent variables. The optimal lag length for the model was determined using the different criterion such as, Akaike Information Criterion (AIC) and Schwarz Bayesian Criterion (SBC). Stationarity of the time series was confirmed through popular tests such as, Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests, with differencing applied where necessary. The reliability of the results was reinforced through multiple diagnostic tests. Residual autocorrelation was assessed using Lagrange Multiplier tests, while heteroskedasticity was examined via White's test. Stability of the VAR system was verified through AR root plots, ensuring all inverse roots of the characteristic polynomial fell within the unit circle. The VAR model offers several advantages for this study. First, it facilitates the detailed analysis of feedback effects between coal, petroleum and CO2 emissions, shedding light on the complex interactions within energy-environment systems. The findings contribute to the sustainable economic development and environmental policy literature by providing region-specific insights, which further suggest targeted mitigation strategies in Guangdong and other regions with comparable energy consumption patterns. An empirical analysis of Guangdong Province's fossil fuel and emission trends yields several key findings. The dataset, comprising 25 annual observations, reveals distinct relationships between energy consumption, and CO_2 emissions.

4. Results and discussions

4.1 Descriptive statistics

Descriptive statistics underscore notable patterns in fossil fuel usage. Coal consumption displays left-skewed distribution, with 74.8% of values (12,513.68 to 13,647 units) exceeding the mean (SD = 4,808.877). This skewness suggests predominantly high consumption levels, interrupted by occasional declines potentially linked to policy interventions or economic fluctuations. Petroleum consumption exhibits greater stability, with a mean of 1,319.851 units and median of 1,518.92 units (SD = 389.003), showing only minor downward variations.

Logarithmic transformation of the data provides crucial insights into CO_2 emission dynamics. Emission levels demonstrate limited variability (mean = 5.835, median = 5.979, SD = 0.486), indicating that fluctuations in fossil fuel consumption have not produced substantial immediate effects. This stability may reflect either gradual atmospheric carbon accumulation or offsetting effects among different emission sources.

All three variables exhibit negative skewness and platykurtic distributions, characterized by flatter peaks and broader tails than normal distributions. Jarque-Bera tests confirm normal distribution ($p > 0.05$ for all variables), validating the suitability of these data for VAR model estimation.

These trends offer significant policy implications. The left-skewed fuel consumption patterns demonstrate that while intensive usage periods dominate, temporary reductions have occurred likely in response to policy changes, economic slowdowns, or infrastructure upgrades. The persistent CO_2 emissions despite fuel consumption variations highlight the challenges in decarbonization and underscore the need for transformative energy policies.

These findings establish a robust foundation for understanding Guangdong's energy-environment nexus, enabling sophisticated econometric analysis of fossil fuel impacts. The subsequent VAR model analysis will build upon these descriptive results to identify dynamic relationships and causal mechanisms among the variables.

Table 1 Descriptive statistics

	CO2 Emission	Coal Consumption	Petroleum Consumption
Mean	12513.68	1319.851	5.8354
Median	13647	1518.92	5.978
Maximum	18439	1676.09	6.506
Minimum	5051	547.19	4.989
Std. Dev.	4808.877	389.00	0.485
Skewness	-0.41	-0.743	-0.455
Kurtosis	1.561	1.94	1.7466
Jarque-Bera	2.88	3.47	2.5023
Probability	0.23	0.176	0.286

4.2 Unit Root Tests and Stationarity Analysis

This study examines the stationarity properties of coal consumption, petroleum consumption, and log-transformed CO_2 emissions using ADF and PP tests. These diagnostic procedures identify potential unit roots that could distort regression outcomes if left unaddressed. Initial testing revealed non-stationarity level forms, a common characteristic of macroeconomic and energy time series data. ADF and PP tests produced insignificant results ($p > 0.05$), confirming the presence of stochastic trends in the original series. This finding necessitated data transformation to assure the stationarity requirement for time series before proceeding empirical analysis.

First-order differencing successfully converted variables to meet stationary series requirements, with both tests yielding statistically significant results ($p < 0.01$). The transformed variables ΔCOAL (coal consumption), ΔPETRO (petroleum consumption), and ΔlnCO2 (log CO_2 emissions) exhibited mean-reverting behavior without unit root contamination. This transformation shows that while energy use and CO2 emissions display long-term trends, their period-to-period fluctuations maintain a constant mean, satisfying stationarity conditions.

The consistent results from both ADF and PP tests strengthen our proceeding for the detailed analysis. This dual verification proves particularly valuable for analyzing Guangdong's energy data, given the region's history of structural changes and market volatility.

The policy implications of these findings are noteworthy. The mean-reverting property of differenced variables suggests that sudden changes in energy consumption or emissions primarily affect short-term growth rates rather than producing lasting

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impacts. This characteristic underscores the need for sustained policy implementation to achieve meaningful, long-term reductions in fossil fuel use and associated emissions.

These stationarity findings provide a robust statistical foundation for subsequent econometric modeling in this research. The rigorous testing approach enhances the study's validity and ensures the results are suitable for both academic inquiry and policy development. The confirmed stationarity of transformed variables enables reliable analysis of Guangdong's energy-emission dynamics through advanced econometric techniques.

Table 2 Stationarity Test Results

Variables	PP (level)	PP (First Difference)	ADF (level)	ADF (First Difference)
CO2 emission	-0.893	-3.120**	-0.890	-3.75**
Coal consumption	-1.353	-3.245**	-1.637	-3.56**
Petroleum consumption	-1.98	-3.42**	-2.463	-3.637**

Note: ***, ** indicate significance levels at 1% and 5%, respectively.

4.3 Johansen cointegration test

The study employed the Johansen cointegration test to assess long-term equilibrium relationships among energy consumption, and CO_2 emissions. Trace test and Maximum Eigenvalue test confirmed one statistically significant cointegrating vector at the 5% significance level. These results reveal a stable long-run relationship between the variables, indicating they move together in equilibrium despite short-term fluctuations. The presence of a single cointegrating vector suggests fossil fuel consumption maintains a consistent long-term association with its environmental impacts. This finding holds crucial importance for developing accurate predictive models that balance energy demand with CO2 emission reduction policies. The cointegration outcome necessitates joint consideration of these variables in the investigation, as it confirms their interdependent dynamics among variables. This empirical relationship suggests valuable insights for policymakers exploring energy consumption patterns with environmental sustainability goals over a period of time.

Table 3 Johansen cointegration test

	Eigenvalue	Trace Statistic	Critical Value	Prob.
None *	0.872	51.23**	39.535	0.003
At most 1	0.560	16.93	22.136	0.109
At most 2	0.326	11.32	13.53	0.131
At most 3	0.041	1.935	4.45	0.15
	Eigenvalue	Max Eigenvalue Statistic	Critical Value	Prob.
None *	0.837	32.011**	22.259	0.002
At most 1	0.367	10.618	16.79	0.532
At most 2	0.353	9.028	10.11	0.232
At most 3	0.009	0.199	3.52	0.982

Notes: **denotes a 5% significant level. Max and Trace tests show that there is at most 1 cointegrating vector.

4.4 The optimal lag period selection

When applying VAR models, selecting the correct lag length is essential, as it directly impacts the accuracy of the estimated results. The optimal lag must be sufficiently long to capture all dynamic economic relationships between variables. Researchers commonly use FPE, Logl, AIC and SC and HQ criteria to determine the best lag length for the VAR model. As shown in Table 4, the LR, FPE, AIC, and HQ tests all identify 2 as the optimal lag length. Accordingly, this study adopts a lag period of 2, as the test results confirm it as the most appropriate choice.

Table 4 lag period selection

Lag	LogL	LR	FPE	AIC	SC	HQ
0	-418.545	NA	1.15e+12	37. 40	38. 8	38.92
1	-320.057	126.20*	1.76e+09	31. 41	32.64*	31.33
2	-309.70	20.68	1.62e+09*	31.490*	33.01	32.25*
3	-301.13	08.28	2.14e+09	33.63	34.04	32.90

Note: * denotes the lag length in a model selected by the criterion

4.5 VAR Estimation Results and Interpretation

The VAR model estimation provides significant insights into the dynamic relationships between energy consumption and CO_2 emissions. Our findings reveals that both coal and petroleum consumption exert statistically significant positive effects on CO2 emissions, leading their

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substantial environmental impact. particularly, coal demonstrates particularly strong carbon-intensive properties, while petroleum shows considerable elastic responsiveness in driving emission growth. These empirical findings suggest conclusive evidence of contaminated fuels' persistent pollution effects, underscoring the urgent need for transitioning to sustainable energy options.

The Johansen cointegration test confirmed a stable equilibrium relationship among the variables, with one variable primarily driving long-term dynamics. This result verifies that energy consumption patterns systematically influence emission trajectories over extended periods. The analytical robustness was enhanced through first-differencing of all variables, enabling precise modeling of both short-term fluctuations and long-term trends in the energy-emission system.

Complementary descriptive statistics further elucidate these relationships. The consistent negative skewness across all variables indicates dominance of higher consumption and emission values, reflecting sustained fuel dependence throughout the observation period. The moderate-to-high variability in coal and petroleum usage patterns suggests fluctuating consumption behaviors attributable to economic factors, technological advancements, and policy changes. These characteristics reveal structural complexities in the energy sector that necessitate targeted policy interventions.

Table 5 VAR estimates

	CO2		CO2		
CO2 (-1)	1.045	Coal Consumption (-1)	9.12e-06	C	-0.801
	-0.3398		-1.85e-05		-1.249
	[3.128]		[0.477]		[-0.563]
CO2 (-2)	-0.419	Coal Consumption (-2)	-4.06E-05		
	-0.375		-2.30E-05		
	[-1.11]		[-1.774]		
Petroleum Consumption (-1)	0.003	R-squared	0.995		
	-0.01	Adjusted R-squared	0.993		
	[1.726]	Akaike AIC	-3.633		
Petroleum Consumption (-2)	-0.046	Schwarz SC	-2.988		
	-0.021				
	[-2.108]				

4.6 Deep learning model and CO2 emission forecasting

This paper employs LSTM deep learning model to forecast CO2 emissions in Guangzhou. Based on available data, initially we confirmed prediction ability of LSTM model using different indicators, such as Root Mean Square Error (RMSE) and R-squared. The results show high accuracy. Table 6 shows the RMSE value is close to zero, confirming high accuracy and minimal error, whereas R2 value is more than 70%, confirming the LSTM model outperform. Figure 1 displays the CO2 emissions predicted by the LSTM model, showcasing both the actual and forecasted results from 1995 to 2030. The black line in the graph represents the historical emissions recorded over the years. From 1995 to 2005, there is a steady increase, reflecting industrial expansion and economic development. Notably, emissions continue to climb until 2025, peaking at 5.57 million tonnes. The red line illustrates the projected emissions from 2022 onward, as estimated by the LSTM model. According to the forecast, emissions are expected to decline consistently after 2025, continuing through 2030.

Table 6 Accuracy metrics

Models	**RMSE**	**R^2**
LSTM	0.860	0.81

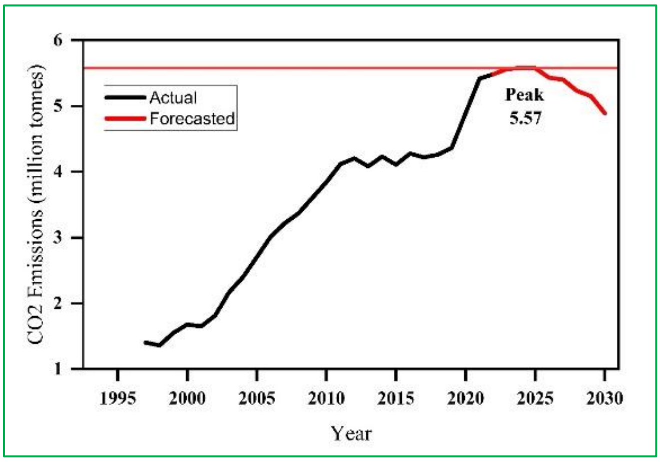

Fig. 1 Forecasting CO2 emissions with LSTM model

5. Conclusion

This study employs VAR technique to investigate the relationship between energy consumption and environmental pollution, particularly CO2 emissions and further forecast CO2 emissions trend in Guangdong over a period of 1997 to 2021. The study found Caol consumption degrading environment, whereas

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petroleum consumption also has a direct impact on environment. This comprehensive investigation uncovers crucial insights into the relationship between coal consumption, petroleum use, and CO_2 emissions. The cointegration analysis confirms fundamental fossil fuel dependence by establishing their stable long-term connection. VAR model estimates reveal significant emission impacts from both coal and petroleum use, with coal particularly driving increased emissions due to its high carbon intensity. The findings underscore the urgent need for strategic shifts toward alternative energy systems that reduce fossil fuel reliance while maintaining energy security.

These results provide vital guidance for policymakers developing evidence-based strategies to balance energy needs with environmental protection. Future research should build upon this work by incorporating renewable energy adoption rates and economic growth indicators to better understand emission drivers. Addressing both energy demands and climate change mitigation requires sustained collaboration across sectors, focusing on sustainable development and conservation initiatives. The empirical evidence from this study of energy-emission dynamics in a key developing region contributes valuable data to ongoing global discussions.

Declarations

Competing interests: The authors declare no competing interests.

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