SUSTAINABILITY CHALLENGES: ENERGY CONSUMPTION AND CARBON EMISSIONS IN THE YANGTZE RIVER DELTA REGION IN CHINA

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Abstract
This study investigated the energy consumption and carbon emissions in the Yangtze River Delta (YRD) region of China, one of the most economically developed and densely populated areas in China. The GDP within the YRD Region exhibited a steady upward trend in recent years, with Jiangsu boasting the highest GDP followed by Zhejiang, Shanghai, and Anhui in descending order. In recent years, energy consumption has significantly increased in the YRD region. industrial sectors have been the primary contributors to this rise, especially in Jiangsu, while Shanghai's energy consumption patterns indicate a strong focus on the tertiary sector. The total carbon emissions in the YRD region generally increased in recent years, and the carbon emissions in Shanghai were the lowest, whereas Jiangsu had the highest carbon emissions. The results demonstrated a substantial link between rising energy consumption and increasing carbon emissions, primarily influenced by the region's significant dependence on economic growth and energy demand. This paper emphasized the necessity for improved energy efficiency measures, the promotion of renewable energy sources, and comprehensive policy frameworks that align economic growth with environmental sustainability in the YRD region of China.

Keywords: Energy consumption; Carbon emissions; Yangtze River Delta (YRD) Region; Economic growth; Energy efficiency

1. INTRODUCTION

China, boasting a population surpassing 1.4 billion and experiencing rapid economic growth, stands as the world's largest developing nation in both populace and economic stature. The rapid economic development relies heavily on substantial consumption of energy (Komarova et al., 2022). As industries expand and infrastructure develops, there is a corresponding increase in the demand for energy to power factories, transportation systems, and residential areas (Xin et al., 2023). In recent years, domestic energy production in China has seen a slow increase due to issues related to fossil energy reserves and associated technology, which falls significantly short of meeting the country's energy consumption demands (Guang and Wen, 2020).

Carbon emissions are significantly related to energy consumption (Ahmadi and Frikha, 2023). The primary sources of energy consumption, such as coal, oil and natural gas, release carbon dioxide (CO_2) when combusted. Higher energy consumption from these sources directly leads to increased carbon emissions. Many industries rely heavily on energy-intensive processes that produce substantial carbon emissions. As energy consumption rises for manufacturing, construction, and other industrial activities, so do carbon emissions (Wesseling et al., 2017). According to the statistical data from the website: http://www.statista.com, China was the biggest emitter of carbon dioxide (CO_2) emissions in 2022, accounting for nearly 31 percent of the global emissions, which can be attributed to the following key factors: (i) China relies heavily on coal for energy consumption and industrial processes, (ii) over the past few decades, China has undergone rapid

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industrialization, leading to increased energy consumption in manufacturing, construction, and other sectors, which in turn drives up CO_2 emissions, (iii) the growing number of vehicles and reliance on fossil fuels for transportation contribute significantly to carbon emissions, and (iv) Although China is investing heavily in renewable energy, the transition from fossil fuels to renewable energy sources is still ongoing, and fossil fuels continue to dominate the energy mix (Yu et al., 2024).

Therefore, China faces two major challenges: a critical energy shortage and environmental pollution issues, both of which raise significant concerns for the nation's sustainable development and environmental welfare (Long et al., 2023). China is addressing both energy shortage and carbon emissions through some strategies like encouraging diverse energy sources, improving efficiency, modernizing infrastructure, promoting conservation, implementing market-based mechanisms, and international collaboration (Wang et al., 2024). To tackle the issue of massive carbon emissions, China announced the 'dual carbon' goal, which referred to China's commitment to both peak carbon emissions by 2030 and achieve carbon neutrality by 2026 (Jia et al., 2022). This initiative aims to address climate change by reducing carbon emissions as well as promoting sustainable development. To achieve the dual carbon goals, China is expected to focus on a range of measures, including the share of renewable energy sources in its energy mix, improving energy efficiency, implementing carbon pricing mechanisms, and investing in clean technology and infrastructure (Cai et al., 2023; Jiang et al., 2024).

There existed some studies on the energy consumption and carbon emissions in literature. Chen et al. (2023) conducted a systematic investigation into the driving forces and pathways to mitigate carbon emissions in China. They discovered that energy substitutions and energy conservation technologies have a positive impact on reducing carbon emissions. Ji et al. (2023) calculated and analyzed the energy consumption and carbon emissions in Shanghai from 2011 to 2019, and concluded that while energy consumption and carbon emissions in Shanghai increased steadily, the intensities of both energy consumption and carbon emissions gradually declined. Ji (2024) conducted a comprehensive study on energy production, consumption, carbon emissions, and available agricultural residues for energy and environmental benefits in China and proposed potential applications of agricultural residues for energy production and carbon sequestration using pyrolysis conversion. The Yangtze River Delta (YRD) region in China holds pivotal importance in the nation's development as a key economic hub, exerting substantial influence on China's economic expansion and industrial progress (Kuai et al., 2024). In literature, there is a notable absence of studies and corresponding analyses regarding energy consumption and carbon emissions in the Yangtze River Delta (YRD) region of China.

Hence, the primary aim of the present paper is to systematically compute and analyze the energy consumption, as well as energy-related and process-related carbon emissions, in the YRD region of China. To achieve this, this paper is organized into several key sections. First, the data source and relevant analytical methods (including the methods for estimating energy consumption and carbon emissions) are briefly introduced. Following this, the results are presented, where the economic situation, energy consumption and carbon emissions in the YRD region of China are analyzed and discussed. Finally, the practical implication for solving the challenges of rising energy consumption and carbon emission in the YRD region of China and a summary of our findings are provided.

2. DATA SOURCE AND ANALYTICAL METHOD

2.1. General introduction of the YRD region

The YRD Region, encompassing Shanghai and its surroundings, stands as a pivotal urban hub within China's economy, consistently driving significant growth and innovation. (Miao et al., 2022). In addition to the municipality of Shanghai, the YRD Region consists of the provinces of Jiangsu, Zhejiang, and Anhui, as shown in Figure 1. The entire YRD Region spans an area of 0.36 million square kilometers. Nowadays, the YRD region is the richest region per capita in China. In 2023, the YRD region generated a gross domestic product (GDP) of 30.51 trillion-yuan, accounting for nearly 24% of the total GDP in China. The YRD region, covering 4% of China's land area, generated nearly one-quarter of the national economic output. The population of the region totals approximately 235.22 million people, accounting for 16.66% of China's total population. Due to its unique geo-economic advantages in urbanization and industrialization, the YRD region, known for its high degree of

openness, accounts for one-third of China's imports and exports (Quan et al., 2021). Some basic information of the YRD region in China is summarized in Table 1.

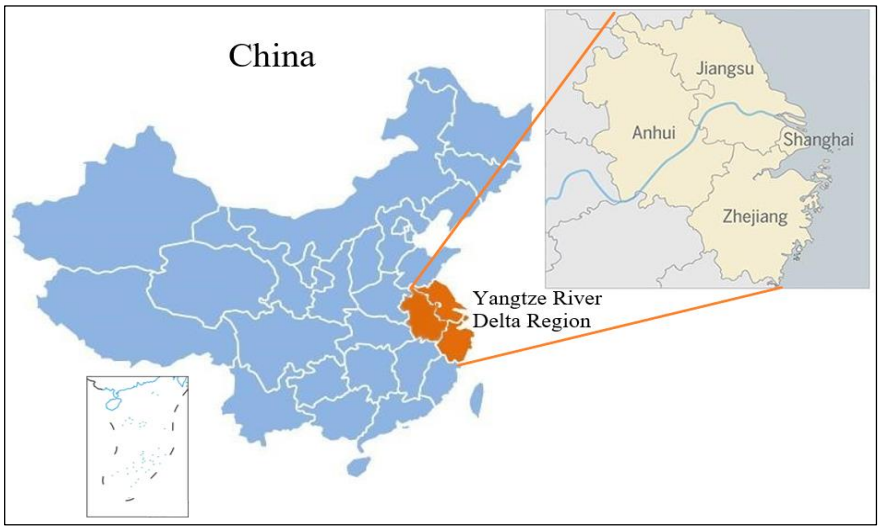

FIGURE 1 - MAP OF THE YED REGION IN CHINA

TABLE 1 - GENERAL INFORMATION OF THE YRD REGION IN CHINA [A]

Item	Shanghai	Jiangsu	Zhejiang	Anhui	Total
Area / (104 km2)	0.63	10.72	10.55	14.01	35.91
People / (million people)	24.75	85.15	65.77	61.27	236.94
GDP / (trillion yuan)	4.47	12.29	7.77	4.50	29.03
Energy consumption / (million tce)	116.83	358.24	291.12	158.83	925.02

[a] data in 2022. [b] tce is the abbreviation of ton of standard coal equivalent.

In 2019, China introduced the Master Plan for Integrated Regional Development of the YRD region to promote urban-rural integration, develop high-tech industries, enhance infrastructure, protect the ecological environment, and improve public services by 2025 with a focus on uniting the YRD region (Shi et al., 2022), which can promote the sustainable development of the Yangtze River Delta region.

2.2. Data source

The study utilizes economic and energy data sourced from multiple editions of the China Statistical Yearbook, China Energy Statistical Yearbook, as well as the statistical yearbooks of Shanghai, Jiangsu, Zhejiang, and Anhui across different years.

2.3. Calculation method for energy consumption

Energy serves as a foundational catalyst for both economic advancement and societal progress, with a well-established interdependence between energy availability and socio-economic development (Bologna, 2013). The progress of urbanization and industrialization comes with the trade-off of increased energy consumption and environmental degradation (Qureshi et al., 2016). Thus, changes in economic and social structures positively affect the environmental degradation, urging countries to make a transition from non-renewable energy to renewable energy (Wang et al., 2022). The consumption of energy, particularly from burning fossil fuels, results in significant carbon emissions (Zhang et al., 2022). The increase in global temperatures due to energy-related carbon emissions presents a pressing issue on a worldwide scale (Wu et al., 2020). Thus, accurately assessing energy consumption is essential for quantitatively analyzing economic development and environmental impact.

Energy consumption encompasses various energy sources such as raw coal, clean coal, coke, fuel oil, gasoline, kerosene, and so on. Typically, various energy sources are measured in different units. A variety of units are

utilized to measure different energy sources, such as joule, exajoule, ton of oil equivalent, barrel equivalent, terawatt-hour, and ton of coal equivalent (tce). This study considers tce as the unit of energy sources. The conversion coefficients of various energy sources are taken from the appendix "Conversion Factors from Physical Units to Coal Equivalent" in the "China Energy Statistical Yearbook", as listed in Table 2. Those conversion coefficients of different energy sources are determined based on the calorific values of various energy sources and standard coal (Huang et al., 2021).

TABLE 2 - CONVERSION COEFFICIENTS OF STANDARD COAL EQUIVALENTS FOR VARIOUS ENERGY SOURCES [A]

Energy source	Conversion coefficients of standard coal equivalent	Unit
Raw Coal	0.7143	tce/t
Washed Coal	0.9000	tce/t
Coke	0.9714	tce/t
Crude Oil	1.4286	tce/t
Fuel Oil	1.4286	tce/t
Gasoline	1.4714	tce/t
Kerosene	1.4714	tce/t
Diesel	1.4571	tce/t
Liquefied Petroleum Gas	1.7143	tce/t
Refinery Gas	1.5714	tce/t
Natural Gas	1.3300×10-3	tce/cu.m
Coke Oven Gas	0.6143×10-3	tce/cu.m
Water Coal Gas	0.3571×10-3	tce/cu.m
Coal Tar	1.1429	tce/t
Benzene	1.4286	tce/t
Heat	0.0341×10-3	tce/Mjoule
Electricity	0.1229×10-3	tce/kW·h

[a] China Energy Statistical Yearbook (2023)

The total energy consumption can be calculated using the following formula:

$$Total\_EC = \sum_i \left(EC_i \times C\_TCE_i \right) \qquad (1)$$

where *Total_EC* represents the total consumption of energy, EC_i represents the consumption of the *i*-th energy source, and C_TCE_i is the coefficient of standard coal equivalent for the *i*-th energy source.

2.4. Calculation method for carbon emissions

The consumption of energy would lead to the emissions of greenhouse gases (GHGs), particularly carbon dioxide (CO_2). Generally, carbon emissions from the usage of primary energy can be approximated by applying standard carbon emission factors corresponding to the consumption of different types of energy products (Ji et al., 2023):

$$CEEC = \sum_i \left(EC_i \times C\_TCE_i \times CEF_i \right) \qquad (2)$$

where *CEEC* represents the emissions of carbon from energy consumption (ton of CO_2, tCO_2), CEF_i represents the carbon emission factor for the *i*-th energy source in the form of standard coal (tCO_2/tce).

In this study, the carbon emission factors for various energy sources are sourced from the Intergovernmental Panel on Climate Change (IPCC), which was created in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in order to provide governments at all levels with scientific information. Table 3 lists commonly used carbon emission factors for various energy sources for the estimation of carbon emissions in numerous related studies. For example, Shan et al. (2018) employed the IPCC method to calculate carbon emission inventories in China and obtained the energy-related carbon emissions from 17 fossil fuels in 47 socio-economic sectors. Li et al. (2018) also used the IPCC method to estimate carbon emissions from iron-containing commodities in China and other countries from 2010 to 2015.

TABLE 3 - CARBON EMISSION FACTORS FOR VARIOUS ENERGY SOURCES [A]

Energy source	Carbon emission factor (tCO_2/tce)
Raw Coal	0.7559
Crude Oil	0.5854
Fuel Oil	0.6185
Gasoline	0.5538
Kerosene	0.5714
Diesel	0.5821
Natural Gas	0.4438

[a] the 2006 IPCC Guidelines for National Greenhouse Gas Inventories

3. RESULTS AND DISCUSSION

3.1. GDP in the YRD region

Figures 2(a) and 2(b) depict the GDP trends in Shanghai, Jiangsu, Zhejiang, and Anhui individually, and in the YRD region of China from 2015 to 2022, respectively. The GDP data for three provinces and one city within the YRD Region exhibited a steady upward trend, with Jiangsu boasting the highest GDP followed by Zhejiang, Shanghai, and Anhui in descending order. Despite Shanghai having a smaller geographical area compared to Anhui, its GDP surpasses that of Anhui due to the following factors (Liu et al., 2020): (i) Shanghai has a higher concentration of lucrative industries such as finance, technology, and manufacturing, which contribute significantly to its economic output, (ii) Shanghai's well-developed infrastructure, including transportation networks and port facilities, likely facilitates greater trade and economic activity compared to Anhui, (iii) Shanghai can attract more domestic and foreign investment due to favorable government policies, incentives, and a business-friendly environment, and (iv) Shanghai's status as an international financial and trade center likely provides access to global markets and opportunities, driving economic growth beyond its geographical boundaries. From Figure 2(b), the rapid increase in GDP in the YRD region in China is from 2015 to 2022 can be observed, which can be attributed to the following factors (Yang, 2024): (i) the YRD region has been a key beneficiary of economic reforms and liberalization policies implemented by the Chinese government, (ii) the YRD region has attracted significant foreign direct investment, leading to the development of industries, infrastructure, and business, thus driving economic expansion, (iii) the rapid urbanization and modernization of the YRD region have spurred growth in various sectors, such as finance, real estate, technology, and manufacturing, contributing to its increased economy, (iv) as a major international port and financial center, Shanghai has flourished as a hub for global trade and commerce, further boosting the economic output of the YRD region, and (v) supportive government policies, including incentives for innovation, entrepreneurship and industry development, have fostered an environmental conductive to economic prosperity of the YRD region.

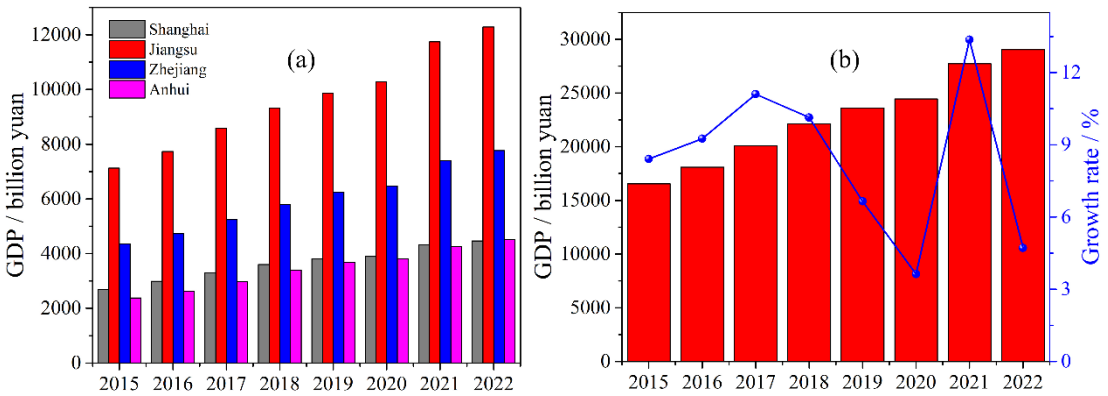

FIGURE 2 - (A) GDP DATA OF SHANGHAI, JIANGSU, ZHEJIANG, AND ANHUI, AND (B) TOTAL GDP DATA OF THE YRD REGION IN CHINA FROM 2015 TO 2022

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3.2. Energy consumption in the YRD region

The development of the economy in a region is intricately linked to its energy consumption (Zhang et al., 2023). Energy serves as a fundamental driver, powering various sectors and enabling economic activities. The importance of energy consumption in economic development is evident in several key aspects: industries depend on energy for production, transportation and communication networks require energy for efficiency, technological advancements and economic growth are linked to energy availability, daily activities and quality of life are influenced by energy access, and energy-intensive industries play a role in driving economic growth (Camarero et al., 2015). Although energy consumption drives economic growth, increasing attention is being paid to its environmental impact. Thus, it is essential to strike a balance between economic progress and the adoption of sustainable and clean energy practices to ensure long-term prosperity (Cai et al., 2024).

Figure 3 shows the total energy consumption in Shanghai, Jiangsu, Zhejiang, and Anhui from 2015 to 2022. The data from Figure 3 illustrates a notable rise in energy consumption across Shanghai, Jiangsu, Zhejiang, and Anhui from 2015 to 2022. The increase in energy consumption in the YRD region stems from various factors such as economic progress, population expansion, urbanization, industrialization, technological advancements, rising vehicle numbers, and increased reliance on public transportation (Deng et al., 2008).

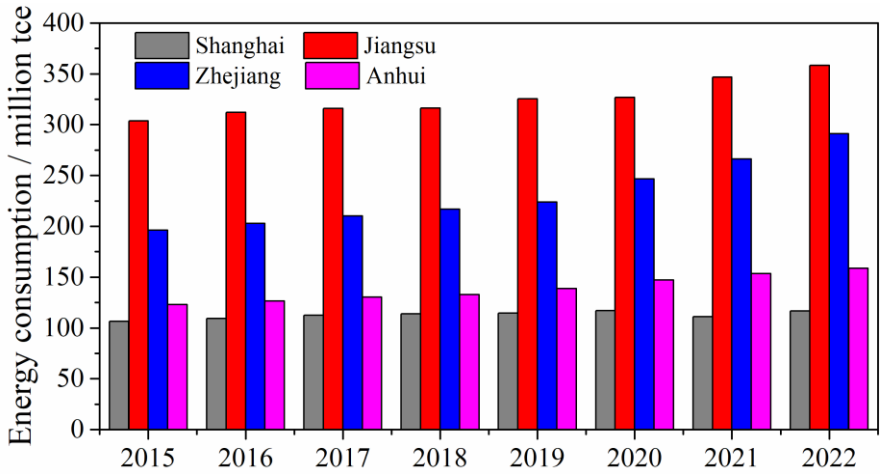

FIGURE 3 - TOTAL ENERGY CONSUMPTION IN SHANGHAI, JIANGSU, ZHEJIANG, AND ANHUI FROM 2015 TO 2022

Figure 4 displays the energy consumption by sector in Shanghai, Jiangsu, Zhejiang and Anhui in 2022. The data presented in Figure 4 highlights the critical role of the industrial sector in energy consumption across the YRD region, particularly in Jiangsu. With an impressive 70.9% share of total energy consumption, Jiangsu's heavy reliance on industrial processes reflects its status as a manufacturing powerhouse. This significant energy consumption is indicative of not only the quantity of production but also the region's commitment to maintaining economic growth through industrial activities. The relationship between energy consumption and economic output is well-documented, suggesting that policies aimed at optimizing energy use within this sector can enhance efficiency without compromising growth (Zhang and Li, 2023). In contrast, the energy consumption patterns in Shanghai reveal the prominence of the tertiary sector, especially in areas such as transportation, storage, postal and telecommunication services, wholesale and retail trade, and catering. The dominance of the third industry in Shanghai indicates a strategic shift towards service-oriented economic activities, which often require different energy profiles compared to traditional industrial sectors (Zhu and Zhang, 2021). This trend may reflect broader changes in urban economies where services increasingly drive economic growth. The differences in energy consumption patterns between regions underscore the unique economic landscapes within the YRD. While Jiangsu's industrial focus aligns with traditional models of economic development, Shanghai's service-oriented economy symbolizes modernization and diversification. Such variations suggest that energy policy must be tailored to regional contexts to effectively support sustainable development goals (Shah et al., 2022). For instance, Jiangsu might benefit from investments in cleaner technologies within industrial operations, while Shanghai could explore energy-efficient solutions in transportation and logistics to support its burgeoning service sector.

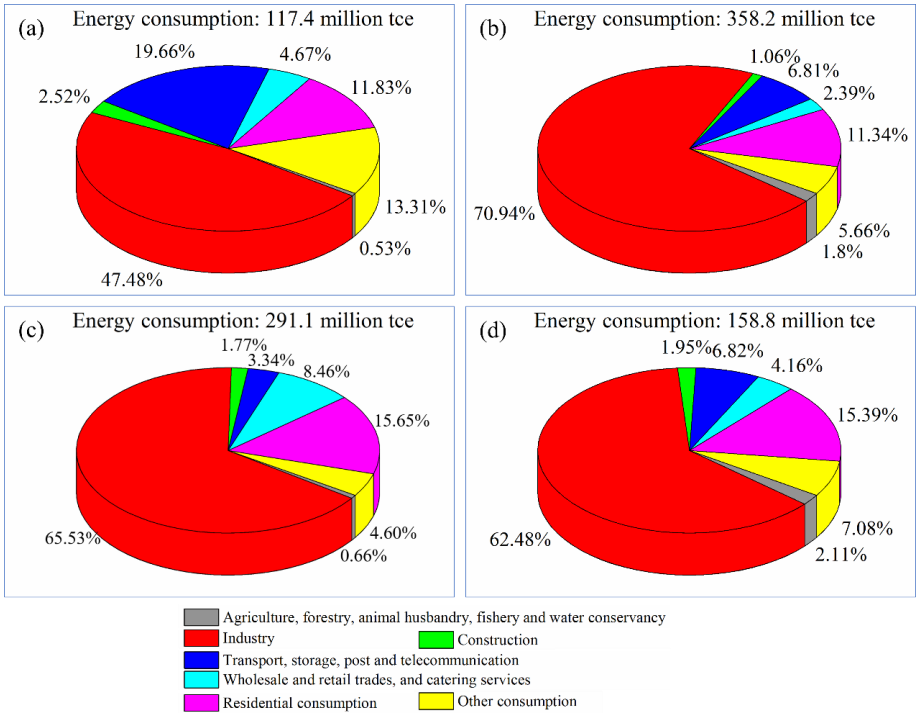

FIGURE 4 - ENERGY CONSUMPTION BY SECTOR IN (A) SHANGHAI, (B) JIANGSU, (C) ZHEJIANG, AND (D) ANHUI IN 2022

3.3. Carbon emissions in the YRD region

According to the energy consumption data and the carbon emission factors of various energy sources, the carbon emissions from energy consumption in Shanghai, Jiangsu, Zhejiang and Anhui can be estimated, as shown in Figure 5. From Figure 5, it can be observed that (i) carbon emissions in Shanghai in various years were the lowest, whereas Jiangsu had the highest carbon emissions, and (ii) Zhejiang and Anhui provinces had carbon emissions levels that were comparable to each other, situated between those of Shanghai and Jiangsu. The total carbon emissions from energy consumption in the YRD region are shown in Figure 6. The trend of increasing total carbon emissions from energy consumption in the YRD region from 2015 to 2022, with the exception of a decline between 2020 and 2021, presents significant implications for both environmental policy and regional economic strategies. The gradual rise in carbon emissions during the earlier years may reflect the YRD region's robust industrial activity, urban expansion, and increased energy demand driven by economic growth. As one of China's most economically dynamic areas, the YRD region has been characterized by rapid industrialization, contributing substantially to its carbon footprint. The pandemic had short-term effects on industrial output and energy consumption patterns worldwide, and lockdowns and reduced economic activities during 2020 could have led to temporary reductions in emissions in the YRD region as well.

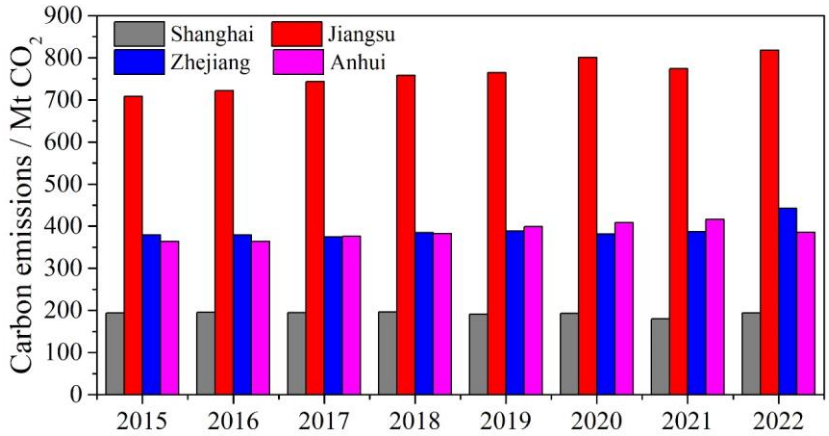

FIGURE 5 - CARBON EMISSIONS FROM ENERGY CONSUMPTION IN SHANGHAI, JIANGSU, ZHEJIANG AND ANHUI FROM 2015 TO 2022

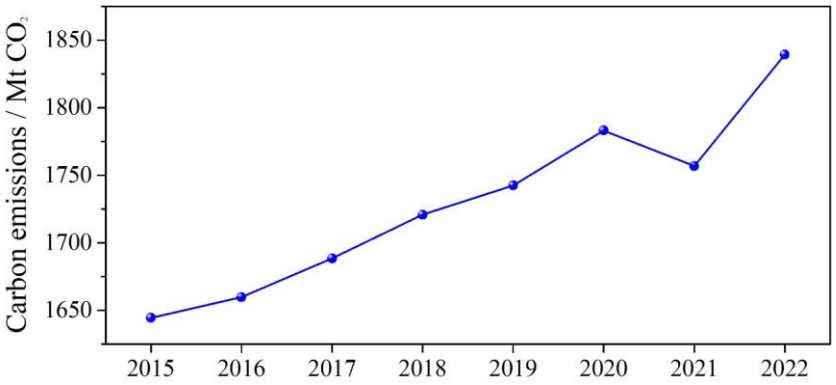

FIGURE 6 - TOTAL CARBON EMISSIONS FROM ENERGY CONSUMPTION IN THE YRD REGION FROM 2015 TO 2022

4. PRACTICAL IMPLICATION

To address the challenges of increasing energy consumption and carbon emissions in the YRD region of China, a comprehensive strategy is crucial. First, policymakers should prioritize the transition to renewable energy sources, such as solar, wind, and hydropower, by investing in infrastructure and incentivizing private sector participation. Implementing stricter regulations on fossil fuel use and promoting energy efficiency across industries can significantly reduce carbon footprints. Additionally, enhancing public transportation systems and encouraging the adoption of electric vehicles will help decrease emissions from the transportation sector. Urban planning initiatives that focus on sustainable development and green building practices can further mitigate energy demand. Finally, raising public awareness about energy conservation and climate change can foster community engagement and encourage behavioral changes that contribute to lower energy consumption. By integrating these strategies, the YRD region can effectively tackle its energy and emission challenges while promoting sustainable economic growth.

5. CONCLUSION

In this study, the energy consumption and carbon emissions in the YRD region of China were calculated and analyzed. In recent years, the YRD region has experienced steady GDP growth, with Jiangsu leading in economic output, followed by Zhejiang, Shanghai, and Anhui in that order. All three provinces and one city showed a marked increase in energy consumption, predominantly driven by industrial sectors, particularly in Jiangsu. Shanghai's energy consumption patterns reflect a strong emphasis on the tertiary sector. The total carbon emissions in the YRD region have generally risen, with Jiangsu recording the highest carbon emissions, while Shanghai reported the lowest emissions. This study highlighted a clear relationship between increased energy consumption and rising carbon emissions, primarily driven by the region's dependence on economic growth and energy demand. This paper underscores the urgent need for improved energy efficiency initiatives, the advancement of renewable energy sources, and the development of comprehensive policy frameworks that support the alignment of economic growth with environmental sustainability in the YRD region.

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