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## Research article

## Assessing the environmental impacts of renewable energy sources: A case study on air pollution and carbon emissions in China

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## ABSTRACT

This study investigates the impact of renewable and non-renewable energy sources on carbon emissions in the context of China's 14th Five-Year Plan (2021–2025). The plan emphasises a “Dual-control” strategy of simultaneously setting energy consumption limits and reducing energy intensity for GDP (gross domestic product) in order to meet the targets of the five-year plan. Using a comprehensive dataset of Chinese energy and macro-economic information spanning from 1990 to 2022, we conduct a Granger causality analysis to explore the relationship between energy sources and the level of air pollution. Our findings reveal a unidirectional link, wherein renewable energy contributes to a reduction in air pollution, while non-renewable energy sources lead to an increase. Despite the government's investment in renewable energy, our results show that China's economy remains heavily reliant on traditional energy sources (e.g., fossil fuels). This research is the first systematic examination of the interplay between energy usage and carbon emissions in the Chinese context. Our findings provide valuable insights for policy and market strategies aimed at promoting carbon neutrality and driving technological advancements in both government and industries.

## 1. Introduction

Air pollution, originating from both anthropogenic and natural sources, presents significant challenges and carries numerous potential risks to both economic development and human health (Zhu et al., 2020). Based on the Global Burden of Disease (GBD) research, 6.7 million deaths were attributed to indoor and outdoor pollution worldwide in 2019, and of these, 4.3 million people died prematurely because of outdoor air pollution (Roser, 2021). Prior studies (e.g., Goodkind et al., 2020; Mujtaba and Shahzad, 2021) have indicated that if not effectively controlled, air pollutants will continue to pose a threat to human health.

Innovation in renewable technology<sup>1</sup> has the potential to enhance

the efficiency of existing fossil fuels, thus reducing the consumption of energy during the manufacturing process (He and Shen, 2017; Miremadi et al., 2019; Zhang et al., 2023). The most commonly used renewable energy sources are biomass from plants, geothermal energy, hydro-power, solar energy, and wind energy. Miremadi et al. (2019) found that innovation could improve the technological level of renewable energy, providing a boost in production. Innovation in renewable energy technologies can help in providing clean energy to the market and can advantageously affect energy portfolios (Dogan et al., 2020; Zhu et al., 2020). Despite this, relatively little attention has been given to the causal relationship between renewable and non-renewable energies and air pollution.

Moreover, China represents a significant case study in the global

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<sup>1</sup> We define renewable energy as sources of energy that are naturally replenished and can be harnessed without causing depletion or significant environmental harm. Examples of renewable energy include biomass, geothermal, hydroelectric, solar, and wind (Dogan et al., 2020; REN21, 2021). On the other hand, non-renewable energy refers to sources that are finite and cannot be replenished within a human timeframe, resulting in their eventual depletion. These sources often involve extracting and burning fossil fuels, e.g., coal, natural gas, and oil, which can contribute to environmental pollution and climate change (Pham et al., 2020).

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context to understand the causal relationship between renewable and non-renewable energy sources and air pollution. As the second-largest economy in the world, China's rapid economic growth has been heavily reliant on the use of substantial amounts of fossil fuels (Zhou et al., 2019). Examining the impact of renewable and non-renewable energy sources on air pollution in China can provide valuable insights into the effectiveness of different energy strategies in mitigating environmental risks and promoting sustainable development. To date, China is the largest methane emitter in the world, with methane emissions accounting for around 26% of the world's total emissions. According to Zheng et al. (2020), in 2020, China's carbon emissions accounted for about 30% of global emissions. This is one of the ways in which China has caused varying levels of air pollution across the country (Jia et al., 2022; Zhu et al., 2020). There is increasing evidence that air pollutants, for instance, PM<sub>2.5</sub>, are spreading beyond China's densely populated areas (e.g., Beijing, Guangdong, and Shanghai) and additionally, air pollutants are increasing at a higher rate in China than they are in developed countries (e.g., the USA, and Western Europe) and developing countries (e.g., Pakistan), especially during the wintertime period (Li et al., 2014). It is significant to note that air pollutants are capable of traversing, via airflow beyond national boundaries (Lv et al., 2019). The Chinese air pollution problem is, therefore, closely connected to the global issue of air pollution.

In an effort to combat pollution and protect the environment, China has taken a number of top-down policy measures. For example, during the 75th United Nations General Assembly in 2020, President Xi made a major announcement that China is aiming to reach carbon dioxide neutrality by 2030 and achieve carbon emissions reduction by 2060 (McGrath, 2020; Yang et al., 2021). Coupled with this was the intention to provide increased investment in developing green energy technologies (Ao et al., 2023). According to the National Action Plan, several major metropolitan areas (e.g., Beijing, Hebei, and Tianjin) are listed as priority areas for reducing air pollution. A key element of the action plan for cleaner air production is the use of innovation in renewable energy technologies (Lin and Zhu, 2019; Tang et al., 2023; Zhu et al., 2020). Air pollution and carbon emissions in China contribute to climate change through the release of greenhouse gases from non-renewable energy sources like coal. This intensifies the greenhouse effect, leading to rising temperatures, changing precipitation patterns, and more extreme weather events. Promoting renewable energy and sustainable practices is crucial in mitigating these environmental challenges and reducing the harmful effects of air pollution on the environment and human health.

It is noteworthy that several aspects of renewable energy are receiving increased attention following COP26 and COP27 (e.g., Adekoya et al., 2023). Despite this, there are relatively few empirical studies have investigated the contribution of renewable energy to the reduction of China's air pollution. In one recent study, Zhu et al. (2020) empirically investigated the spatial pattern of air pollution in 31 Chinese provinces based on innovations in renewable energy technologies. Technology innovations in renewable energy were found to reduce the concentrations of respirable suspended particles (PM<sub>10</sub>) and nitrogen oxides (NO<sub>x</sub>). Our study extends prior research by empirically examining the impact of renewable and non-renewable energies on carbon emissions in China. It would be advantageous to examine a causal relationship between different sources of energy and air pollution in order to determine whether the time series data of energy consumption is useful for forecasting air pollution in longer term. As far as we are aware, there has been no empirical study, particularly using Granger causality analyses, to investigate the impacts of renewable and non-renewable energies on national-level air pollution in China.

In order to address this gap, we analyse the innovation diffusion of energy supply and carbon emissions in China, using Chinese quarterly energy and macroeconomics time series data between 1990 and 2022. We employed the ARIMA (Autoregressive Integrated Moving Average) regression model and found that, first, air pollution and GDP in China have increased over time. Second, renewable energy reduces

greenhouse gas emissions after controlling for economic growth, population growth, and coal prices (the main energy source in China). Third, non-renewable energy increases both CO<sub>2</sub> and greenhouse gas emissions after accounting for population growth, economic growth, and the price of coal (the primary energy source in China). Fourth, based on additional analyses, our findings indicate that the impact of the selection of energy sources on air quality is unidirectional, meaning air pollution does not act as an indicator for the Chinese government to take corrective measures to increase renewable energy use. We also find that greenhouse gas emissions and CO<sub>2</sub> emissions are significantly and negatively impacted by renewable energy. Carbon dioxide and greenhouse gas emissions are positively impacted by non-renewable energy sources. Fifth, we find no evidence for the reverse relationship. In other words, China's economy still relies heavily on traditional energy sources (e.g., fossil fuel) despite the government's decision to invest in renewable energy sources. Therefore, air pollution level does not affect the government's decision to increase (or decrease) use of renewable energy.

This study offers several contributions to the literature on the relationship between public policy and application of energy source. This is the first study to examine the impact of both renewable and non-renewable energies on air quality. Our finding extends prior evidence (e.g., Chien et al., 2021; Doğan et al., 2020; Hailemariam et al., 2022; Li et al., 2021), and shows that use of renewable energy is associated with reducing air pollution and use of non-renewable energy is associated with increasing air pollution. Although prior studies provide useful insights that both developed and developing economies are not immune to environmental problems (e.g., air pollution), they predominantly focus on the implications of asset pricing and investment strategies (Tang et al., 2023; Zhang et al., 2023). Second, our research offers a more nuanced perspective to the ongoing debates surrounding the extent to which escalating air pollution levels in China influence the government's efforts to prioritise renewable energy adoption while discouraging the utilisation of non-renewable sources. By engaging in critical discussions and incorporating diverse viewpoints, our study not only expands upon existing literature on renewable energy (e.g., Ao et al., 2023; Lu et al., 2020; Zheng et al., 2020; Zhu et al., 2020), but also encourages a deeper understanding of the complex interplay between environmental challenges and policy responses. Lastly, this study enriches the environmental management literature (e.g., Doğan et al., 2020; Nasir et al., 2021; Pham et al., 2020) by critically examining China's energy landscape, a crucial case study due to its far-reaching influence on global energy markets, its burgeoning prominence as a leader in renewable energy implementation, and the intricate nature of its energy portfolio and policy framework. By delving deeper into the multifaceted aspects of China's energy sector, our research fosters more comprehensive and critical discussions, paving the way for a broader understanding of the challenges and opportunities that arise within the context of environmental management and sustainable development.

This study has significant practical and theoretical implications that shed light on the benefits of renewable energy investment. Our findings emphasise several key areas of impact, including improvements in public health, reductions in greenhouse gas emissions, enhanced energy security, and reductions in pollution (Lin and Zhu, 2019; VoPham et al., 2018; Zhou et al., 2019). Our research shows that non-renewable energy sources are a major contributor to greenhouse gas emissions, leading to climate change and other negative impacts such as extreme weather events, habitat destruction, and decreased productivity. By examining the case of China, our study serves as guidance for other developing nations in achieving a harmonious balance between economic expansion and environmental protection. The insights derived from our results hold significance for policymakers, industry stakeholders, and researchers, who are actively involved in shaping and informing sustainable energy strategies. Despite China's efforts to promote renewable energy since the 2000s, air pollution remains a persistent issue, with negative repercussions worsening faster than corrective actions taken.

The remainder of this paper is organised as follows: Section 2 delves into the relationship between air pollution, renewable energy, and health, with a specific focus on China, encompassing the country setting, theoretical underpinnings and the development of our hypotheses. Section 3 details the research design and methodology, including the empirical model and the sample and data used. Section 4 presents the empirical results, offering additional testing and a robustness check to support our findings. Finally, in Section 5, we offer our conclusions, policy implications, limitations of the study, and we set out recommendations for future research.

## 2. The relationship between air pollution, renewable energy, and health: a FOCUS ON China

In this section, we provide a comprehensive examination of the rationale for choosing China as the research context. We discuss the significance of studying China's energy landscape, due to its unique combination of rapid economic growth, environmental challenges, and ambitious policy goals. This context offers valuable insights into the interplay between renewable energy use, air pollution, and the complexities of balancing economic development and environmental sustainability. Furthermore, we explore four theories (Environmental Kuznets Curve theory, the Pollution Haven Hypothesis, the Porter Hypothesis, and Energy Efficiency Paradox theory) and two hypotheses on environmental regulation of air pollution and renewable energy usage.

Throughout the literature review, several themes, patterns, and trends emerged. Firstly, there is a growing recognition of the negative environmental consequences associated with non-renewable energy sources, particularly in terms of air pollution and greenhouse gas emissions (Hailemariam et al., 2022; Sharifzadeh et al., 2019; Zhang et al., 2023). This recognition has spurred global efforts to transition towards renewable energy alternatives. Secondly, the relationship between economic growth and environmental quality, specifically air pollution, is a topic of significant interest. Scholars (e.g., Fan and Hao, 2020; Pinzón, 2018; Saint Akadiri et al., 2019; Yuan et al., 2015) have explored the complex dynamics between economic development, energy consumption, and environmental degradation, highlighting the need for sustainable energy strategies to mitigate adverse impacts. Finally, the role of environmental regulations in promoting renewable energy adoption and reducing air pollution has gained prominence. Studies (Ao et al., 2023; Chien et al., 2021) have demonstrated the effectiveness of stringent regulations in driving the transition towards cleaner energy sources and improving air quality. By synthesising the existing literature, our study contributes to this knowledge base and sheds light on the specific context of China, providing valuable insights for policymakers, researchers, and stakeholders seeking to promote sustainable energy practices and address air pollution challenges.

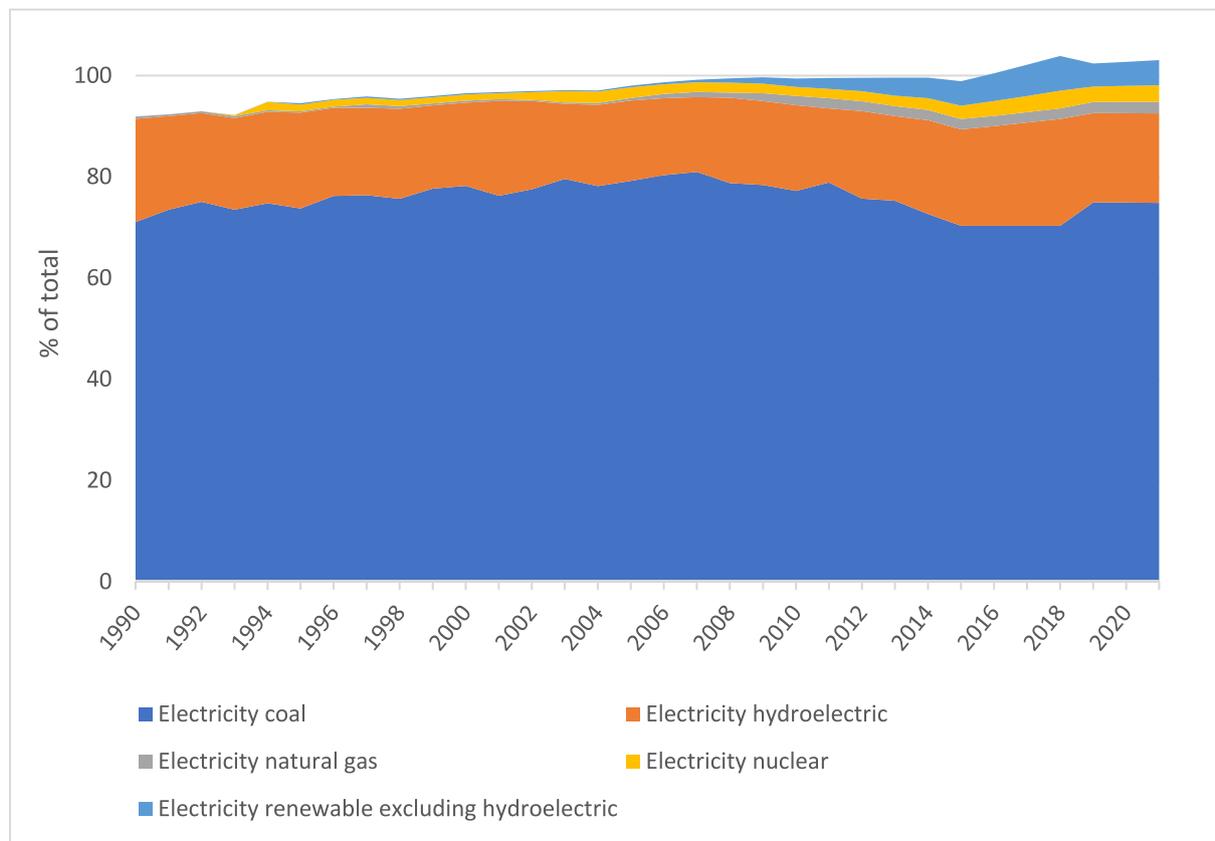
### 2.1. Country setting – a focus on China

We have four main arguments to support the motivation for a single country context and the representation of the Chinese case. First, China's status as the world's biggest energy consumer and emitter of greenhouse gases highlights the importance of understanding its energy policies within the context of global climate change initiatives and the transition to cleaner energy sources (Hepburn et al., 2021; Sharifzadeh et al., 2019). Furthermore, as of 2020, China has installed 281 GW of wind power and 253 GW of solar energy sources, making it the world's leading producer of wind power and solar energy (Liu et al., 2011). Under the 14th Five-Year Plan, the Chinese government has set ambitious targets for the adoption of renewable energy that include increasing non-fossil fuel consumption to 20% by 2025, reaching peak carbon emissions by 2030, and achieving carbon neutrality by 2060 (Hepburn et al., 2021). To support these targets, the Chinese government provides generous subsidies and incentives for renewable energy projects, including feed-in tariffs (FITs), tax incentives, subsidy

programs (e.g., subsidies for solar photovoltaic, installations, and wind power projects) and preferential loans (Song et al., 2022).

To emphasise China's role in renewable energy, it is worth noting that the country has made substantial investments in renewable energy over the last decades and has become one of the world's largest manufacturers of technologies related to renewable energy, including electric vehicles, solar panels, and wind turbines (see Li and Taeihagh, 2020; Ahmad et al., 2021; Fan and Hao, 2020). China is committed to improving energy efficiency, reducing costs, and promoting innovation. These efforts are reflected in China's global investments in renewable energy projects (Hepburn et al., 2021; Sharifzadeh et al., 2019; Tiwari et al., 2022), which accounted for about 28% of global investment in renewable energy in 2020 (REN21, 2021). This investment is not limited to China, but also extends to other countries through initiatives like the Belt and Road Initiative, which strives to advance economic collaboration and infrastructure expansion in Asia, Europe and Africa (Anwar et al., 2021; Wu et al., 2020). Through this initiative, China has invested in renewable energy projects in various countries, including Pakistan, Kazakhstan, and Egypt. Despite these efforts, China's heavy reliance on coal for electricity generation remains a major obstacle to achieving its renewable energy targets. Coal still accounts for over 70% of China's energy mix (See Fig. 1) and reducing its dependence on coal remains a daunting task. China's rapid economic growth and urbanisation have also led to increased energy demand, representing a barrier to the expansion of renewable energy sources. Nevertheless, investments in renewable technologies have reduced China's dependence on fossil fuels and helped to lower greenhouse gas emissions. China aims to reduce its carbon footprint by 2060, with renewable energy sources expected to produce over 60% of the country's electricity by 2030 and up to 86% of total electricity by 2050, according to the International Renewable Energy Agency (IRENA, 2020). Therefore, China's energy landscape and policies have important implications for global efforts to address climate change and transition to cleaner energy sources. While the government sets ambitious targets for renewable energy usage and invests heavily in the research and development of renewable energy technologies, reducing dependence on coal, and transitioning to a low-carbon economy remains a significant challenge (Fan and Hao, 2020). Studying China's experiences with renewable energy can provide researchers and policymakers insights into best practices for scaling up these technologies and integrating them into national energy infrastructure making it an important case to study.

China wields significant influence in the worldwide fossil fuel industry, owing to its substantial deposits of coal, oil, and natural gas. As such, comprehending China's energy demand, and supply patterns, and its policies concerning fossil fuel use, is crucial in projecting global energy markets and forecasting future trends in energy consumption and emissions. With its significant reserves of coal, oil, and natural gas, China is a powerful player in the global fossil fuel market, as well as a substantial contributor to greenhouse gas emissions, responsible for almost 30% of global carbon dioxide emissions (Le Quéré et al., 2020 and Chaudhry et al., 2021). China's energy policies related to fossil fuel use are shaped by various factors, including economic development, energy security and environmental concerns. For example, China's reliance on coal for electricity generation has led to high levels of air pollution and greenhouse gas emissions, which have serious implications for public health and climate change (Adekoya et al., 2023; Hasan et al., 2021; VoPham et al., 2018). However, the Chinese government has also taken steps to lessen its reliance on fossil fuels and promote cleaner energy sources, including implementing a national carbon trading scheme, setting strict emissions standards for coal-fired power plants, and discouraging the use of coal mines and coal-fired power plants. For example, in 2016, China announced plans to close more than 1000 coal mines (Reuters, 2016), and in 2017, it ordered the closure of more than 100 million tons of steel production capacity and 50 million tons of coal production capacity (Reuters, 2017). Additionally, China has invested heavily in nuclear power and clean coal technologies,



**Fig. 1.** China's Total Power Generation by various energy sources  
Source: The World Bank and National Bureau of Statistics of China databases.

which include carbon capture and storage (CCS) (EIA, 2021). In 2020, China consumed 4997 million metric tons of oil equivalent (Mtoe) of energy, making it one of the world's biggest energy consumers (BP, 2021). However, China's energy mix is slowly shifting towards cleaner sources, with non-fossil fuels accounting for 28.2% of primary energy consumption in 2021, up from 27.8% in 2020 (see Fig. 1). Hence, understanding China's energy landscape and policies related to fossil fuels is crucial to global efforts to combat climate change and transition to cleaner energy sources.

Fourth, China's energy mix is complex and transforming the energy sector involves a multitude of factors, including government policies, market forces, technological developments, and social and cultural attitudes towards energy use. While China has made noteworthy strides in boosting the proportion of renewable energy sources in its energy portfolio, it still relies heavily on fossil fuels, particularly coal, for electricity generation. One key challenge in China's energy transition is the need to balance economic growth with environmental sustainability (Zhou et al., 2019; Yang et al., 2021). China's explosive economic growth in recent decades has led to a massive surge in energy consumption, which has largely been met through the expansion of coal-fired power plants. However, this has also led to severe air pollution, which has become a major public health concern in many parts of the country (e.g., Beijing, and Taiyuan) (Li et al., 2014; Lv et al., 2019). In response, the Chinese government has implemented a range of policies to promote cleaner energy sources and reduce emissions, including setting ambitious targets for renewable energy adoption and imposing stricter emissions standards for coal-fired power plants. Another factor shaping China's energy transition is the country's efforts to promote energy security and reduce its dependence on foreign oil and gas imports (He and Shen, 2017). China has significant reserves of coal, oil, and natural gas, and has traditionally relied on these resources to meet its energy needs. However, as the global demand for oil and gas continues

to rise and prices become increasingly volatile (Naeem et al., 2022), China has broadened its energy sources to decrease its reliance on imported non-renewable fuels. Thus, wind, solar, and hydropower have become more prominent domestic sources of renewable energy. In spite of these endeavors, China's energy transition continues to confront significant obstacles. One major challenge is the intermittent nature of renewable energy sources such as wind and solar, which can impede their integration into the power grid and lead to problems with grid reliability and energy reduction. Additionally, the environmental impacts of large-scale hydropower projects, such as displacement of local communities and destruction of ecosystems, have raised concerns among environmental advocates (Jelti et al., 2021). Studying China's energy transition can yield useful perspectives on the political, economic and social factors that shape energy policy and influence the deployment of different energy technologies. By understanding the complex and evolving nature of China's energy mix, researchers and policymakers can develop more effective strategies for promoting renewable energy adoption and reducing greenhouse gas emissions, both in China and around the world.

## 2.2. Theories and hypotheses on air pollution and renewable energy usage

There are four prominent theories (e.g., Environmental Kuznets Curve theory, the Pollution Haven Hypothesis, the Porter Hypothesis, and Energy Efficiency Paradox theory) that provide a framework for understanding the relationship between air pollution and renewable energy usage, elucidating factors that drive changes in pollution levels over time.

### 2.2.1. The impacts of economic growth on air pollution and renewable energy usage

The Environmental Kuznets Curve (EKC) theory posits that pollution

levels initially rise as countries experience economic growth, but eventually peak and decline as higher development levels are achieved (Pan et al., 2023; Shen et al., 2023). This relationship, however, may not always hold true, as other factors, such as income levels, industrialisation and urbanisation can impact pollution levels. For example, European countries have generally adopted more stringent environmental regulations, driven by higher income levels, public demand, and regional coordination through the European Union (Dogan et al., 2020; Halkos and Tsilika, 2019; Pham et al., 2020; Saint Akadiri et al., 2019). These factors have contributed to a more advanced stage on the EKC curve, where pollution levels have started to decline with increased development. As an example, in a study conducted by Saint Akadiri et al. (2019) on renewable energy sources across the 28 member states of the EU from 1995 to 2015, the correlation between macroeconomic indicators and the feasibility of achieving long-term environmental sustainability was explored. Their findings show a long-term bidirectional causal relationship between economic growth and the adoption of renewable energy, indicating that the use of renewable energy could potentially mitigate environmental pollution sustainably. In contrast, China's position on the EKC curve is more ambiguous, as its rapid economic growth has been accompanied by severe air pollution levels. However, the introduction of recent government policies, such as the Renewable Energy Law 2006, the National Renewable Energy Development Plan (2016–2020), electric vehicle incentives, the green certificate trading system and FITs, encourage use of renewable energy and implement stricter environmental regulations (Shen et al., 2023). In a study by Yuan et al. (2015), the relationship between energy consumption, economic growth, and air pollution, in both developed and underdeveloped regions of China, was analysed. The study revealed that economic growth has a negative impact on air pollution concentrations. Other studies (e.g., Fan and Hao, 2020; Pan et al., 2023; Yuan et al., 2015) also found similar results. These policies, incentives, and research findings suggest that China may be moving towards the turning point on the EKC curve. This turning point signifies a decline in pollution levels as economic development increases.

The Energy Efficiency Paradox theory suggests that advances in energy efficiency could result in increased energy consumption, negating pollution reduction gains. In relation to renewable energy and air pollution, we use the paradox to explore whether rising renewable energy use corresponds to reduced energy consumption and subsequent improvements in air quality (Eom et al., 2020; Shen et al., 2023). Furthermore, some researchers suggest that air pollutants are transregional and transnational in nature (Halkos and Tsilika, 2019; Zhu et al., 2020). Zhu et al. (2020) provided a detailed analysis of renewable energy and air pollution across 31 Chinese provinces between 2011 and 2017 and concluded that regional policymakers should consider the spatial distribution of renewable energy resources in China. Furthermore, Halkos and Tsilika (2019), based on an analysis of 49 countries, asserted that transboundary air pollution systems that comprise source and receptor are interconnected. Therefore, air pollutants may be transported from one country to another. Also, it is crucial to account for potential rebound effects and the influence of broader consumption patterns. For example, as China shifts towards a service-based economy, the demand for energy-intensive industries may decrease, but the demand for energy-intensive services (e.g., air conditioning and transportation) may increase, leading to increased energy consumption and negating any gains in reducing pollution (Yuan et al., 2015). According to Jelti et al. (2021), cleaner fuels are more efficient in producing low levels of PM10 and PM2.5 emissions than non-renewable fuels. Additionally, Li et al. (2021) argued that as China's economy grows, its increasing demand for resources and energy could influence consumption patterns in other countries due to its role as the world's largest producer and consumer of goods. Countries like the US, Japan, Australia, and those in Asia, rely on China as a source of raw materials and finished goods. Changes in China's energy consumption patterns and resource use can have ripple effects on the global economy and

environment. As a major player in international climate negotiations and a growing investor in overseas renewable energy projects, the economic growth of China could influence the energy consumption and resource use of other countries that rely on Chinese imports, such as India, Indonesia, Europe, and North America (Fan and Hao, 2020; Li and Taeihagh, 2020). Thus, we hypothesise:

**H1.** As China's economy grows, there is a negative relationship between the use of renewable energy and the level of air pollution.

### 2.2.2. *The impacts of environmental regulations on air pollution and renewable energy usage*

The Pollution Haven Hypothesis suggests that countries without stringent environmental regulations often attract industries with higher pollution output, ultimately leading to higher pollution levels. This hypothesis implies that environmental regulations can have a negative impact on a country's economic competitiveness by driving away industries that generate pollution (Liu et al., 2023; Wang et al., 2019). It is crucial to recognise the intricate interplay of economic and political factors that may impact the relationship between renewable and non-renewable energy sources and air pollution. China's rapid economic growth and industrialisation has led to increased pollution levels (Ao et al., 2023; Lu et al., 2020). Their relatively lax environmental regulations have historically attracted industries that were more heavily polluting, such as the automobile industry (e.g., General Motors, Volkswagen, and Toyota), and companies including Apple, Microsoft, and Intel, both domestically and from overseas, who were seeking to reduce their production costs. This has inevitably contributed to China becoming a pollution haven, resulting in severe environmental consequences including air and water pollution (Li and Taeihagh, 2020). However, as China shifts towards cleaner industries and recognises the importance of sustainable development, it has implemented more stringent environmental regulations, including the 2018 Environmental Protection Tax Law, the 2018 Blue Sky Protection Campaign, and the 2015 Water Pollution Prevention and Control Action Plan. These regulations are intended to curb pollution levels and promote sustainable development in the country. Zhu et al. (2020) suggested that China's policymakers must take into account the spatial distribution of renewable energy resources in different regions, which can vary considerably, to promote cleaner energy sources and combat pollution effectively. Lu et al. (2020) argued that the use of renewable energy can improve air quality management in China through the support of central to local authorities. As a result, some heavily polluting industries (e.g., cement factories, coal-fired power plants, and steel mills) have been closed down while cleaner technologies have been promoted (e.g., renewable energy sources and electric vehicles) (Wang et al., 2019). The risk is that this may cause some of these polluting industries to relocate to other countries (e.g., Vietnam, Bangladesh and Indonesia) where there are more relaxed regulations, thus perpetuating the pollution haven effect.

In contrast, the Porter Hypothesis suggests that environmental regulations can enhance competitiveness and promote innovation. Stricter regulations can drive companies to invest in research and development for more efficient and cleaner production processes. As China enforces more stringent environmental regulations, this could drive innovation and competitiveness in the Chinese market. According to Liu et al. (2023) and Wang et al. (2019), companies in China are investing in research and development for cleaner production methods and adopting sustainable practices, leading to the growth of renewable energy, electric vehicle manufacturing, and other green industries (e.g., ecological tourism, green building and construction materials). China's commitment to international climate agreements, such as the Paris Agreement, and agreements from COP27, further encourages the adoption of cleaner technologies and a low-carbon economy (Chien et al., 2021; Lin and Zhu, 2019; Zhu et al., 2020). The Porter Hypothesis suggests that China's stricter environmental regulations have the potential to stimulate innovation and enhance competitiveness in the long run,

particularly in the area of renewable energy development and the reduction of air pollution levels. Thus, we hypothesise:

**H2.** The implementation of stricter environmental regulations by the Chinese government will increase the use of renewable energy sources and Granger-causes (reduce) air pollution levels.

### 3. Research design and methodology

#### 3.1. Empirical model

To investigate the effect of energy sources on air pollution, we employ the ARIMA (Autoregressive Integrated Moving Average) regression model as our baseline. Following Huang et al. (2019) and Torbat et al. (2018), we formulate Equations (1) and (2) to examine the relationship between energy sources and air pollution:

$$AirPollution_t = \beta_0 + \beta_1 Renewable_t + \gamma' Controls_t + \varepsilon_t, \quad (1)$$

$$AirPollution_t = \beta_0 + \beta_1 NonRenewable_t + \gamma' Controls_t + \varepsilon_t, \quad (2)$$

where  $Renewable_t$  is the independent variable which measures the quarterly proportion of renewable energy in total final energy consumption, while  $NonRenewable_t$  is the independent variable which measures the quarterly proportion of non-renewable energy production from oil, gas and coal sources in total final energy consumption, in time  $t$ .  $AirPollution_t$  is the main dependent variable, which measures the quarterly degree of air pollution in China. We use two time-series variables to capture the air pollution: 1) CO<sub>2</sub> emission refers to the emissions of carbon dioxide measured in kiloton, resulting from the burning of fossil fuels and the manufacturing of cement, and 2) Greenhouse gas emissions are measured in kt of CO<sub>2</sub> equivalents that include all sources of anthropogenic CH<sub>4</sub>, N<sub>2</sub>O and F-gases (HFCs, PFCs and SF<sub>6</sub>), biomass burning (e.g., decay of drained peatlands, forest fires, peat fires, and post-burn decay), but excluding short-cycle biomass burning (e.g., savanna burning and agricultural waste burning).

$Controls_{i,t}$  is the vector of control variables that capture key macro factors that are commonly related with the air pollution. These control variables include the price of coal which is the main energy source in China, GDP which measures the production of goods and services, export amount which measures the production due to foreign demand, and Chinese population. See Appendix 1 for variable definitions.

To ensure that the impact of renewable and non-renewable energy source to air pollution is unidirectional, we use the Granger causality test on the dependent and independent variables. The Granger causality test, first proposed by Granger (1969), is a popular statistical test for verifying whether one time-series variable can forecast another (Pinzón, 2018; Olaoye et al., 2020; Wang et al., 2019). A variable  $X$ , that changes over time, is said to Granger-cause another variable  $Y$ , which also evolves over time, if both  $X$ 's own past values and  $Y$ 's own past values can make better predictions than only  $Y$ 's own past values. In our case, we investigate a two-way effect between energy sources and air pollution. In our analysis, we investigate whether energy sources have a Granger-causal effect on air pollution or vice versa. We conduct two sets of tests to assess the accuracy of predictions for air pollution and energy sources. Firstly, we examine whether incorporating past values of both air pollution and energy sources improves the accuracy of air pollution predictions compared to solely considering its own past values. Secondly, we investigate whether incorporating past values of both air pollution and energy sources enhances the accuracy of energy source predictions compared to solely considering their own past values. Following Berger (1995), we employ the Granger causality tests presented as Equation (3) for both scenarios

$$y_t = \alpha_0 + \sum_{j=1}^n \alpha_j y_{t-j} + \sum_{j=1}^n \beta_j x_{t-j} + \gamma z_t + \varepsilon_t \quad (3)$$

where  $y_t$  is the dependent variable at  $t$ ,  $x_{t-1}$  is the independent variable at  $t-1$ , and  $z_t$  is the set of control variables.

In our modeling approach, we employ both ARIMA models and Granger causality tests. ARIMA models are widely used and effective for time series forecasting, offering several advantages (Pack, 1980). Firstly, they can handle various types of univariate time-series data. Secondly, ARIMA models can accommodate different patterns, including linear or nonlinear trends, constant or varying volatility, and seasonal or non-seasonal fluctuations. Thirdly, they are straightforward to implement and interpret, requiring minimal parameters and assumptions. However, ARIMA models also have limitations and drawbacks (Morita et al., 2013). Firstly, they are unable to capture interactions and dependencies between variables, limiting their ability to account for external factors' effects on the time-series. Secondly, ARIMA models assume the data is normally distributed and homoscedastic, which may not hold true for all time-series data. On the other hand, Granger causality is a widely employed method for studying causal relationships between random variables (Granger, 1969). It offers the advantage of identifying directional influences between variables without any prior hypothesis on the involved subnetworks (Beharelle and Small, 2016). However, it is important to note that Granger causality tests have their weaknesses. They require the data to be stationary and cannot be performed on non-stationary data. Additionally, they are unable to provide forecasts when there are interdependencies between multiple variables.

By incorporating both ARIMA models and Granger causality tests, we aim to capture the strengths of each method and gain a comprehensive understanding of the dynamics and causal links within the examined time series data.

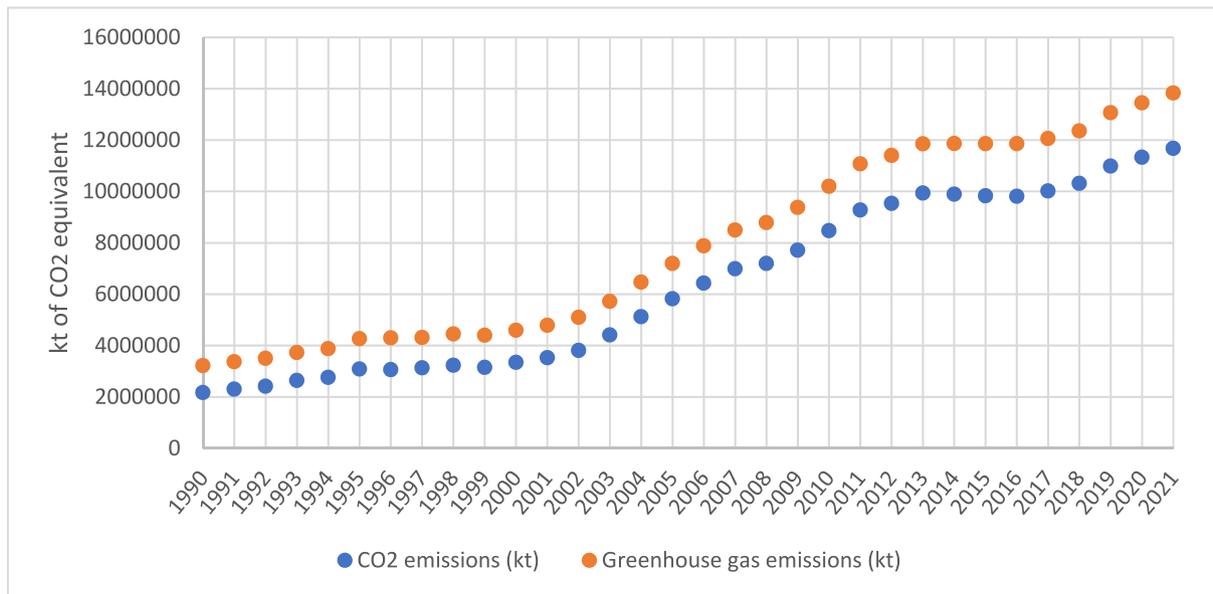
#### 3.2. Sample and data

We collected quarterly energy and macroeconomic time series data for China from the World Bank and National Bureau of Statistics of China databases, covering the period from 1990 to 2022. This sample period is chosen for three main reasons. Firstly, it encompasses crucial policy milestones and shifts in China's energy policy, including the introduction of the Five-Year Plans and the increased emphasis on renewable energy (Wang et al., 2020; Sharifzadeh et al., 2019). This offers valuable insights into the impact of policy interventions on energy supply and carbon neutrality. Second, this sample period includes important global climate agreements, such as the United Nations Framework Convention on Climate Change (UNFCCC), Kyoto Protocol, the Paris Agreement, and Glasgow Climate Pact. Analysing China's energy supply and carbon neutrality during this period helps to evaluate China's progress in meeting its international climate commitments. Lastly, the period from 1990 to 2022 offers a wealth of data on energy supply, consumption, and carbon emissions, making it a suitable choice for investigating energy supply and carbon emissions in China. To reduce the impact of outliers on our data, we apply a winsorisation technique to all continuous variables at the 1st and 99th percentile. Our sample size consists of 128 quarterly observations, which is appropriate for ARIMA models. The general guideline for ARIMA models is to have at least 50 observations, but ideally more than 100 observations to account for seasonal variations and effects (Box et al., 2015). Therefore, our sample size of 128 quarterly observations is sufficient for our data analysis.

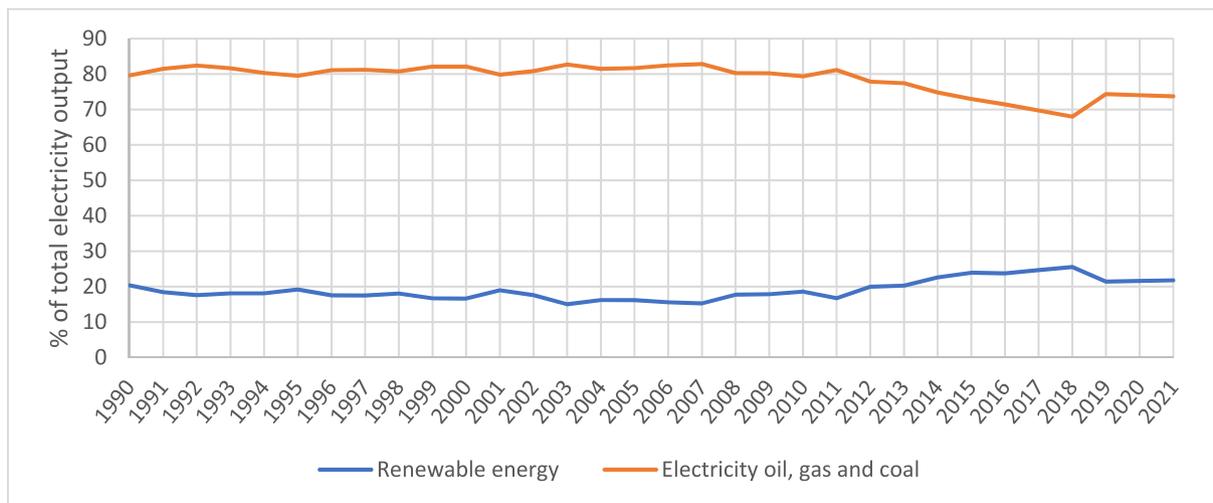
Table 1 offers descriptive statistics for these variables. Means of CO<sub>2</sub> emission and greenhouse gas emission are 1,589,139 kt and 1,974,339 kt, respectively, over the sample period. Our results suggest that China faces significant challenges in carbon neutrality (Lu et al., 2020; Shen et al., 2023). The fact that greenhouse gas emissions are always higher than CO<sub>2</sub> emissions (see Fig. 2) indicates that China needs to address, not only CO<sub>2</sub> emissions, but also other greenhouse gases such as methane and nitrous oxide. Our results are consistent with existing studies (e.g., Hepburn et al., 2021; Li et al., 2021; Yang et al., 2021). We include four control variables to capture key factors that are commonly known to

**Table 1**  
Descriptive statistics.

Variables	Obs	Mean	Std. Dev.	Min	Max
CO <sub>2</sub> Emission	128	1,589,139	823,403.5	543,340	2,925,000
LogCO <sub>2</sub> Emission	128	1.686,712	0.065,577,925	1.584,283	1.793,526
Greenhouse	128	1,974,339	917,588	805,567.5	3,450,000
LogGreenhouse	128	1.71182	0.054,303,125	1.6,270,405	1.785,211
Renewable	128	18.79127	2.83503	15.03704	25.54805
NonRenewable	128	79.22868	3.994,484	67.98457	82.84348
CoalRents	128	0.295,926	0.2,849,875	0.0156,994	1.238,028
GDP (in trillion)	128	9.766,143	7.2,307,675	1.59,949,825	24.6016
LogGDP	128	3.363,988	0.0919,846	3.20151	3.498,255
Export	128	278.071	241.485,825	15.52275	661.9958
LogExport	128	2.952,005	0.151,322,525	2.6,982,575	3.19883
Population (million)	128	1286.032	77.69928	1135.185	1402.76
LogPopulation	128	9.108,474	0.0265,675	9.055067	9.146,983



**Fig. 2.** China air pollution over years  
Source: The World Bank and National Bureau of Statistics of China databases.



**Fig. 3.** Renewable vs. non-renewable energy output in percentage  
Source: The World Bank and National Bureau of Statistics of China databases.

affect the relationship between the independent and the dependent variables. These controls include (1) the price of coal which captures the cost of the main energy source in China, (2) GDP which captures the production of goods and services, (3) the export amount which captures the production due to foreign demand, and (4) Chinese population which captures the main usage of energy. Means of renewable energy proportion and of non-renewable energy proportion are 18.79% and 79.23%, respectively. Our study reveals that China still heavily relies on non-renewable energy sources, consistent with the findings of previous research (Shen et al., 2023; Wang et al., 2019) that attribute China’s reliance on coal, oil, and natural gas to economic growth and industrialisation. These results underscore the need for continued efforts to shift towards cleaner energy sources in China. Fig. 3 displays the trends of both energy sources over the sample period, suggesting that China has made some progress in promoting the use of renewable energy sources.

In Table 2, we present the pair-wise correlations between the variables of our study. Despite the presence of several significant correlations across different pairs of variables, no correlation value between independent variable and control variable is high enough to warrant any concern about multicollinearity. We checked for possible multicollinearity by estimating the variance inflation factors (VIFs) for all variables. Our results show that all the VIFs are less than 2, indicating that our regression estimates are not affected by multicollinearity (Chatterjee and Hadi, 2015).

#### 4. Empirical results and discussions

##### 4.1. Baseline results

ARIMA model addresses the economic growth because along with the sample period, China had experienced a fast growth in economic. We select this particular period to examine the impact of energy sources towards air pollution. Table 3 presents the ARIMA regression results of our baseline models of Equations (1) and (2). Columns (1) and (2) of the table employ CO<sub>2</sub> emissions as the dependent variable, while columns (3) and (4) utilize greenhouse gas emissions as the dependent variable. These results indicate that for every kiloton increase in the use of renewable energy, log of CO<sub>2</sub> emission in China reduces by 1.035% and log of greenhouse emission reduces by 1.55%. Meanwhile, for every kiloton increase in the use of non-renewable energy, log of CO<sub>2</sub> emission in China increases by 0.713% and log of greenhouse emission increases by 0.984%. These findings are in line with our H1, that as China’s economy grows, the adoption of renewable energy sources is negatively related to the level of air pollution. Our results suggest that continued efforts to shift towards renewable energy sources in China could help to reduce the country’s CO<sub>2</sub> and greenhouse gas emissions, thereby contributing to global efforts to reduce carbon footprint by 2060. These efforts could include policies and incentives to encourage the development and use of renewable energy sources, as well as efforts to improve the integration and management of renewable energy into the existing energy infrastructure. Our results are supported by the EKC theory that as China’s economy grows, it is moving towards a stage where higher income levels are associated with cleaner energy sources and lower pollution levels. The results also support findings by Pinzón (2018),

**Table 2**  
Correlation matrix.

Variables	1	2	3	4	5	6	7	8
1 LogCO <sub>2</sub> Emission	1							
2 LogGreenhouse	0.996	1						
3 Renewable	-0.9919	-0.9866	1					
4 NonRenewable	-0.9658	-0.9584	0.9552	1				
5 CoalRents	0.4095	0.4026	-0.4982	-0.388	1			
6 LogGDP	0.9882	0.9892	-0.9658	-0.9732	0.327	1		
7 LogExport	0.9962	0.9907	-0.9884	-0.9805	0.4185	0.9902	1	
8 LogPopulation	0.9677	0.9682	-0.9428	-0.9782	0.296	0.9918	0.9788	1

Olaoye et al. (2020), Wang et al. (2019).

##### 4.2. Granger causality between CO<sub>2</sub> emission and energy sources

Table 4 shows the results of the Granger causality tests between CO<sub>2</sub> emission and two energy sources. We perform four model specifications based on Equation (3). In each model, we adopt the approach suggested by Ferreira (2013) and incorporate two annual lags (t-1 and t-2) as the baseline. Through extensive testing of various lagging structures, we have determined that this specific lag setup strikes a balance by capturing relevant information without sacrificing excessive complexity. Compared to deeper lag structures, this approach avoids the loss of valuable data and ensures the optimal representation of the relationships within the model. In this Granger causality analysis, we focus on the joint significance of the two annual lags of x. It is possible to predict that x is a Granger-cause of y if the two annual lags are significant in the sense that changes in x precede changes in y. Columns (1) and (2) in Table 4 are based on observations of t-1 and t-2 between the dependent variable (CO<sub>2</sub> emission) and independent variable (energy sources). In these baseline regressions, we include coal price, Chinese GDP, Chinese export and Chinese population as control variables. In column (1), CO<sub>2</sub> emission is predicted by its own lags (i.e., LogCO<sub>2</sub>Emission (t-1) and LogCO<sub>2</sub>Emission (t-2)), as indicated by significant F-statistics of 2.777, and the lags of renewable energy (i.e., Renewable (t-1) and Renewable (t-2)), as indicated by significant F-statistics of 1.45. Both sums of lagged coefficients (total of lag t-1 and t-2) are negative and significant, e.g., a one-unit increase of CO<sub>2</sub> emission, and of renewable energy and at t-1, decreases the current CO<sub>2</sub> emission by 3.6816 and 0.00629, respectively. Likewise, column (2) shows that CO<sub>2</sub> emission is predicted by two of its own lags (LogCO<sub>2</sub>Emission (total)), as indicated by significant F-statistics of 3.26, and the lags of non-renewable energy (NonRenewable (Total)), as indicated by significant F-statistics of 2.35. A one-unit increase of CO<sub>2</sub> emission at both t-1 & t-2 decreases current CO<sub>2</sub> emission by 0.055 but a one-unit increase of non-renewable energy at t-1 & t-2 increases the current CO<sub>2</sub> emission by 0.00505.

To check whether CO<sub>2</sub> emission Granger causes energy sources, we retest equation (3) by swapping dependent and independent variables. Columns (3) and (4) in Table 4 are based on two lags of the dependent (energy sources) and independent variables (CO<sub>2</sub> emission). In column (3), renewable energy is not predicted by its own lag, as indicated by insignificant F-statistics of 21.35, and the lags of CO<sub>2</sub> emission, as indicated by insignificant F-statistics of 56.36. Likewise, column (4) also shows that non-renewable energy is not predicted by its own lags, as indicated by insignificant F-statistics of 3.44, and the lags of CO<sub>2</sub> emission, as indicated by insignificant F-statistics of 23.76.

In summary, the Granger causality tests indicate that there is a clear unidirectional causal relationship between the energy sources and CO<sub>2</sub> emissions. Specifically, there is a negative causality of -0.00529 from renewable energy sources to CO<sub>2</sub> emissions, and a positive causality of 0.00505 from non-renewable energy sources to CO<sub>2</sub> emissions. Therefore, our H2 is supported, indicating that the implementation of stricter environmental regulations by the Chinese government has seen a rise in the use of renewable energy sources and has Granger-caused a reduction

**Table 3**  
ARIMA regression.

Variables	LogCO <sub>2</sub> Emit (1)	LogCO <sub>2</sub> Emit (2)	LogGreenhouse (3)	LogGreenhouse (4)
Renewable	-0.01035*** (0.0015)		-0.0155*** (0.0031)	
NonRenewable		0.00713* (0.0042)		0.00984* (0.0058)
Coalrents	-0.00766*** (0.0014)	-0.00375 (0.0023)	0.0012 (0.0057)	0.00706 (0.0044)
LogGDP	0.46142*** (0.0446)	0.461*** (0.0760)	0.713*** (0.1430)	0.719*** (0.1440)
LogExport	0.16722*** (0.0337)	0.417*** (0.0404)	-0.219*** (0.0643)	0.152** (0.0714)
LogPopulation	-3.70459*** (0.4618)	-5.015*** (0.7190)	-2.117 (1.3820)	-4.164*** (1.6010)
Constant	32.53910*** (3.6026)	41.29*** (6.0720)	19.45* (10.8700)	33.29** (13.5900)
Observations	128	128	128	128
Wald chi 2	55,259.62	15,444.67	5282.04	2479.43
sigma	0.00574***	0.00975***	0.0123***	0.0171***

Note: Clustered standard errors in parentheses. \*\*\*p < 0.01, \*\*p < 0.05, \*p < 0.1.

**Table 4**  
Granger causality tests between Carbon dioxide emission and Energy sources (Renewable and non-renewable energies).

Dependent variable	LogCO <sub>2</sub> Emission (1)	LogCO <sub>2</sub> Emission (2)	Renewable (3)	NonRenewable (4)
LogCO <sub>2</sub> Emission (t-1)	-0.31486*** (0.14)	0.205 (0.15)	64.68 (50.54)	3 (6.27)
LogCO <sub>2</sub> Emission (t-2)	-0.0533 (0.33)	-0.260** (0.13)	-8.276 (25.78)	-1.727 (6.45)
<b>LogCO<sub>2</sub>Emission (Total)</b>	<b>-0.36816</b>	<b>-0.055</b>	<b>56.404</b>	<b>1.273</b>
<b>F-statistic</b>	<b>2.777**</b>	<b>3.26**</b>	<b>56.36</b>	<b>23.76</b>
Renewable (t-1)	-0.00917*** (0.00)		1.256*** (0.46)	
Renewable (t-2)	0.00288* (0.00)		-0.279 (0.46)	
<b>Renewable (Total)</b>	<b>-0.00629</b>		<b>0.977</b>	
<b>F-statistic</b>	<b>1.45***</b>		<b>21.35</b>	
NonRenewable (t-1)		0.00395*** (0.00)		0.118 (0.22)
NonRenewable (t-2)		0.0011 (0.01)		0.258 (0.30)
<b>NonRenewable (Total)</b>		<b>0.00505</b>		<b>0.376</b>
<b>F-statistic</b>		<b>2.35***</b>		<b>3.4400</b>
Coalrents	-0.00679*** (0.00)	-0.00433 (0.00)	0.152 (0.16)	0.0877 (0.21)
LogGDP	0.78048*** (0.18)	0.712*** (0.19)	-31.68*** (11.59)	7.248 (11.27)
LogExport	0.34418*** (0.05)	0.334*** (0.05)	-20.10*** (2.22)	-5.686 (3.72)
LogPopulation	-7.02042*** (1.16)	-7.310*** (1.81)	318.4*** (83.44)	-46.64 (98.18)
Constant	58.76436*** (9.58)	60.22*** (15.03)	-2617*** (675.50)	387.1 (818.10)
Observations	126	126	126	126
Wald Test (p-value)	0.000	0.000	0.000	0.000

Note: Clustered standard errors in parentheses. \*\*\*p < 0.01, \*\*p < 0.05, \*p < 0.1.

in air pollution levels. Our findings provide support for the Porter Hypothesis, which posits that transitioning towards renewable energy sources can reduce emissions and improve the quality of our air. Specifically, our results suggest that the implementation of stricter environmental regulations by the Chinese government has led to an increase in the use of renewable energy sources and a corresponding reduction in air pollution levels, as indicated by the Granger causality tests and other studies (Li and Taeihagh, 2020; Liu et al., 2023; Song et al., 2022; Wang et al., 2019). This underscores the potential benefits of policies that promote the adoption of cleaner energy sources, not only for the environment, but also for human health and wellbeing.

#### 4.3. Robustness check - granger causality between greenhouse emission and energy sources

As a robustness check, we performed another set of Granger causality checks on Equation (3) using an alternative dependent variable, Greenhouse gas emission. Table 5 sets out the results of the Granger causality tests between greenhouse gas emission and two energy sources. Similar to Table 4, we perform four model specifications on Table 5 based on Equation (3).

Columns (1) and (2) in Table 5 are based on two lags of the dependent (greenhouse gas emission) and independent variable (energy sources). In column (1), greenhouse gas emission is predicted by its own lags, as indicated by significant F-statistics of 1.44, and the lags of renewable energy, as indicated by significant F-statistics of 2.85. A one-

Table 5

Granger causality tests between Greenhouse gas emission and Energy sources (Renewable and non-renewable energies).

Dependent variable	LogGreenhouse (1)	LogGreenhouse (2)	Renewable (3)	NonRenewable (4)
LogGreenhouse (t-1)	1.24308*** (0.33)	1.297*** (0.25)	-20.02 (17.53)	10.22 (10.89)
LogGreenhouse (t-2)	-0.71994* (0.42)	-0.588*** (0.22)	30.24 (20.59)	-8.169 (10.98)
<b>LogGreenhouse (Total)</b>	<b>0.52314</b>	<b>0.709</b>	<b>10.22</b>	<b>2.051</b>
<b>F-statistic</b>	<b>1.44**</b>	<b>24.55*</b>	<b>25.77</b>	<b>13.22</b>
Renewable (t-1)	0.00174*** (0.00)		0.222 (0.20)	
Renewable (t-2)	-0.00375 (0.01)		0.106 (0.24)	
<b>Renewable (Total)</b>	<b>-0.00201</b>		<b>0.328</b>	
<b>F-statistic</b>	<b>2.85***</b>		<b>10.11</b>	
NonRenewable (t-1)		-0.00462*** (0.00)		0.0465 (0.20)
NonRenewable (t-2)		0.00515 (0.00)		0.311 (0.28)
<b>NonRenewable (Total)</b>		<b>0.00053</b>		<b>0.3575</b>
<b>F-statistic</b>		<b>1.35*</b>		<b>0.45</b>
Coalrents	0.0006 (0.00)	0.00214 (0.00)	-0.152 (0.20)	0.041 (0.22)
LogGDP	0.25802 (0.27)	0.219 (0.28)	-11.33 (15.52)	7.586 (12.14)
LogExport	0.04238 (0.06)	0.0185 (0.07)	-15.47*** (3.06)	-6.038* (3.47)
LogPopulation	-1.28971 (1.58)	-1.029 (1.56)	181.3** (87.54)	-47.87 (77.73)
Constant	11.08605 (11.79)	8.202 (12.43)	-1373** (688.70)	392.5 (635.10)
Observations	126	126	126	126
Wald Test (p-value)	0.000	0.000	0.000	0.000

Note: Clustered standard errors in parentheses. \*\*\*p &lt; 0.01, \*\*p &lt; 0.05, \*p &lt; 0.1.

unit increase of renewable energy and at both t-1 and t-2 increases the current greenhouse gas emission by 0.00201. Likewise, column (2) shows that greenhouse gas emission is predicted by its own lags, as indicated by significant F-statistics of 24.55, and the lags of non-renewable energy, as indicated by significant F-statistics of 1.35. A one-unit increase of non-renewable energy increases greenhouse gas emission by 0.00053 at total of both t-1 and t-2.

To check whether greenhouse gas emission Granger-causes energy sources, we retest equation (3) by swapping dependent and independent variables. Columns (3) and (4) in Table 5 are based on two lags of the dependent (energy sources) and independent variable (greenhouse gas emission). In column (1), renewable energy is not predicted by its own lags and the lags of CO<sub>2</sub> emission. Likewise, column (2) also shows that non-renewable energy is not predicted by its own lags and the lags of greenhouse gas emission.

Overall, the main results of the Granger causality tests suggest there is a full unidirectional causality running between both energy sources and greenhouse gas emissions, including a -0.00201 causality of running from renewable energy source to greenhouse gas emission, and a 0.00053 causality running from non-renewable energy source to greenhouse gas emission. Thus, Tables 5 and 6 appsec1 indicate that both CO<sub>2</sub> emission and greenhouse gas emission are unidirectionally Granger caused by both renewable and non-renewable energy sources. On one hand, the effort of Chinese policymakers on encouraging use of renewable energy has successfully reduced the air pollution. On the other hand, the rising air pollution levels in China have not induced policymakers to advance the pace of implementation of renewable energy sources.

## 5. Conclusion

In this study, we aimed to examine the impact of renewable and non-renewable energies on carbon neutralisation in China, motivated by China's 14th Five-Year Plan (2021–2025) for implementing "Dual-control" to achieve an energy consumption cap and a decline in energy

intensity of GDP. Our study used a large and comprehensive sample of Chinese energy and macroeconomics data over a period of 32 years. Our findings provide important insights into the relationship between energy sources and air pollution in China, which has significant implications for global policy and market debates. Specifically, our Granger causality results show that as China's economy grows, air pollution levels decrease as the use of renewable energy increases. Also, the implementation of stricter environmental regulations by the Chinese government has increased the use of renewable energy sources and this has Granger-caused a reduction in air pollution levels. The results are consistent with both the EKC theory and the Porter Hypothesis. Our findings suggest that China may be approaching the turning point on the EKC, where economic growth leads to an improvement in environmental quality. At the same time, the Porter Hypothesis is supported, showing that the implementation of stricter regulations can incentivise the country to invest in research and development for more efficient and cleaner production processes, which can ultimately lead to improved air quality. These findings have significant international implications for global policy and market debates related to carbon neutralisation and sustainable energy transitions. However, the study also reveals that China's economy still heavily relies on non-renewable energy sources, indicating a need for continued efforts to shift towards cleaner energy sources in the country. The results of this study have important implications for policymakers and industries in China, and globally, emphasising the need for continued investment in renewable energy sources and the promotion of innovation to achieve carbon neutralisation. Overall, the findings of this study contribute to a better understanding of carbon neutralisation and its stimulation through technology and innovation in the context of China.

The implications of renewable energy reducing air pollution are numerous and significant, ranging from improvements in public health to reductions in greenhouse gas emissions and enhanced energy security. By investing in renewable energy, countries can reap a wide range of benefits while also helping alleviate some of the most urgent environmental and economic challenges confronting the world today, such

as climate change (Doğan et al., 2020), resource depletion (Zhang et al., 2023), pollution (Nasir et al., 2021), and population growth (Pham et al., 2020). For policy makers, our findings highlight the importance of replacing fossil fuels with renewable energy sources as it has numerous benefits for the environment and public health. The combustion of non-renewable fuels is a significant source of greenhouse gas emissions, which are accountable for global climate change. Renewable energy sources can decrease these emissions, enhance air quality, and safeguard public health. Additionally, renewable energy sources are typically less affected by price fluctuations and supply disruptions than fossil fuels. By diversifying the energy mix and increasing the use of renewable energy, countries can enhance their energy security and reduce their dependence on imported fossil fuels. Also, governments can effectively address environmental concerns, reduce greenhouse gas emissions, and mitigate the impacts of climate change. Our findings reveal that non-renewable energy sources have a detrimental effect on air pollution, highlighting their significant contribution to global greenhouse gas emissions that drive climate change. For instance, the combustion of non-renewable fuels, such as fossil fuels, causes the emission of carbon dioxide and other greenhouse gases, which accumulate in the atmosphere and trap heat, leading to a rise in global temperatures. This warming phenomenon can trigger various adverse impacts such as extreme heatwaves, droughts, floods, and other severe weather events. The extraction and transportation of non-renewable energy sources can also have negative environmental impacts, such as habitat destruction, water pollution, and soil degradation.

The negative impacts of air pollution and climate change can also have significant economic costs, such as increased healthcare costs, damage to infrastructure, and decreased productivity (Adekoya et al., 2023; VoPham et al., 2018). Stakeholders, including those in the energy industry, can benefit from our research by recognising the market opportunities associated with renewable energy. The transition towards renewable energy sources presents new avenues for growth, innovation, and competitiveness. Stakeholders can align their business strategies with the global shift towards sustainable energy, leading to long-term profitability and reduced environmental impact. Our study underscores the potential economic benefits that can be derived from embracing renewable energy technologies. Overall, while there are some negative implications for air pollution associated with renewable energy production (e.g., the release of pollutants during manufacturing, disposal of renewable energy technologies, and potential impacts on wildlife and ecosystems from large-scale renewable energy projects), these impacts are generally much lower than those associated with fossil fuels. Moreover, they can be effectively managed through meticulous planning and implementation of mitigation measures.

With respect to our study setting, China, as a fast-growing economy, provides an example to other developing nations in achieving a balance between economic expansion and environmental protection. For example, on a firm-level basis, international companies (e.g., HP, Dell, and Apple) are withdrawing their manufacturing facilities from China to move to friendlier shores (e.g., India, Vietnam, and other countries in Southeast Asia) where there is a Zero Covid policy and unstable political environment (Zhang, 2023). If other economies wish to welcome more foreign companies to their countries, they can utilize the findings indicated in this study.

Economic expansion in China has accelerated since China joined the WTO in 2001 (Li et al., 2021). Air pollution accompanied the accelerating wealth accumulation process in China (Lin and Zhu, 2019; Zhou et al., 2019), and the Chinese government implemented various policies and regulations to promote renewable energy adoption since 2000s. For example, the Renewable Energy Law, passed in 2005, prioritises the development and use of renewable energy in energy development. The 12th Five-Year Plan (2020–2025) lays significant emphasis on renewable energy, and the Golden Sun programme provides financial incentives, market promotion, and technological assistance to boost the expansion of the solar energy sector. The proportion of renewable

energy sources has risen from approximately 10% in 1990 to nearly 30% in 2021. Despite these measures taken by China, to cope with increasing air pollution, negative environmental repercussions worsen quicker than the corrective actions taken. Therefore, in the context of the wider society, our research underscores the significance of transitioning to cleaner energy sources for the wellbeing of communities. By reducing air pollution and improving overall environmental quality, the adoption of renewable energy can have positive impacts on public health, quality of life, and ecosystem sustainability. Our study contributes to raising awareness about the benefits of sustainable energy practices and highlights the importance of collective action in addressing global environmental challenges.

In light of the upcoming COP28 summit, it is crucial to consider the international dimensions of the issues surrounding renewable energy and carbon emissions. As developed nations continue to push heavily polluting industries to developing countries (e.g., Vietnam, Indonesia, and Bangladesh), it becomes increasingly important to address the issue of global inequality and ensure that all nations have access to renewable energy sources at an affordable cost. The COP28 agenda highlights the need for inclusive climate action and the importance of collaboration among all nations in achieving a unified global goal. As such, policy-makers and regulators should focus on identifying strategies to promote sustainable development and innovation that can help reduce the cost of renewable energy and ensure accessibility for all countries. This will require the concerted effort and investment of developed nations to support technological advancements that will help to reduce the cost of renewable energy, promote sustainable development, and ultimately achieve a more equitable and sustainable future for all.

Although this study has important implications for theory and practice, it is important to acknowledge some limitations. First, the findings were derived from an investigation of air pollution in China. The updates from COP28 emphasise the importance of collaboration and investment in innovation and technological advancement to support the transition towards a low-carbon economy. Therefore, future research should explore ways to support developing countries in adopting and implementing renewable energy sources while ensuring a fair and equitable distribution of costs and benefits. This could include examining the effectiveness of international climate finance mechanisms, exploring ways to reduce the cost of renewable energy, and assessing the potential for technology transfer and capacity building initiatives. Second, we examine the causal relationship between renewable and non-renewable energies on air pollution, without taking geographical location into account. The agenda for COP28 highlights the importance of the Loss and Damage Agreement and the global goal of adaptation, suggesting that future studies should focus on the effectiveness of these agreements in addressing climate change. Finally, the Food and Agriculture Organisation's plan to reduce emissions from the food and agriculture industry, and their aim to increase funding for innovation in climate-smart agriculture, suggest that future studies should also examine the potential impact of sustainable agricultural practices on reducing air pollution.

#### CRediT authorship contribution statement

**Xihui Haviour Chen:** Writing – original draft, Writing – review & editing, Validation, Resources, Data curation, Visualization, Project administration. **Kienpin Tee:** Conceptualization, Methodology, Software, Validation, Formal analysis, Resources. **Marwa Elnahass:** Supervision, Data curation, Writing – review & editing. **Rizwan Ahmed:** Writing – original draft.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Appendix A

### Appendix 1

#### Table of variable definitions

Variables	Definitions
<b>Independent variables</b>	
CO2Emission	Carbon dioxide emissions are measured in kilotons per quarter as a result of the burning of fossil fuels and the manufacture of cement. Carbon dioxide is produced by the combustion of solid, liquid, and gaseous fuels, as well as the burning of gaseous fuel.
LogCO2Emission	Log of quarterly CO2Emission
Greenhouse	To calculate the quarterly greenhouse gas emissions in kt of CO2 equivalent, CO2 totals are subtracted from short-cycle biomass burning (e.g., agricultural waste burning and savanna burning), but include other biomass burning (e.g., forest fires, post-burn decay, peat fires, and decay of drained peatlands), as well as anthropogenic sources of CH4 and N2O, and F-gases (HFCs, PFCs, and SF6).
LogGreenhouse	Log of quarterly greenhouse gas emissions
<b>Dependent variables</b>	
Renewable	Percentage of renewable energy in total energy consumption
NonRenewable	Percentage of non-renewable energy production from coal, gas, and oil sources
<b>Control variables</b>	
Coal rents	The coal rent is the difference between the price of hard coal and soft coal at world market prices and the total cost of production (as a percentage of GDP).
GDP (in trillion)	The quarterly Gross domestic product (GDP) is calculated as the product of gross value added by all residents of the economy plus any product taxes, minus any subsidies that did not affect product value. It is calculated without deducting depreciation on fabricated assets or for depletion and degradation of natural resources. The data is expressed in constant local currency.
LogGDP	Log of quarterly GDP
Export	The FOB value of goods provided to the rest of the world in current U.S. dollars.
LogExport	Log of quarterly Export
Population (million)	The total quarterly population in China is calculated according to de facto definitions of population, which includes all residents regardless of legal status or citizenship. This is an estimate for the midyear period.
LogPopulation	Log of quarterly Population

Note: All the data used in this study were obtained from the World Bank and the National Bureau of Statistics of China.

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