Energy Proceedings
Vol 32, 2023
ISSN 2004-2965

Moving towards carbon neutrality: an integrated technology-policy framework for sustainable transition of cities

Ru Guo[1,2,3*], Guanghui Shao[1], Linjing Liu[1], Xiaojing Cao[4], Ling Chen[1], Xiangfeng Huang[1,2*]

1 College of Environmental Science and Engineering, Tongji University, Shanghai, 200092, PR China

2 Institute of Carbon Neutrality, Tongji University, Shanghai 200092, China
3 Shanghai Institute of Pollution Control and Ecological Security, Shanghai 200092, P.R. China
4 Jumbo Consulting, Shanghai, 200035, PR China(*Corresponding author: ruguo@tongji.edu.cn; hxf@tongji.edu.cn)

ABSTRACT

Carbon neutrality roadmaps for cities in developing countries are completely different from those in developed countries due to historical, social, and economic limitations. Taking Shanghai as a case, this study proposes a new framework for sustainable net-zero carbon transition of cities in developing countries by integrating multiple purposes within multiple sectors under carbon budget constraints. The results show that 1) the total carbon emissions of Shanghai decreased from 2010 to 2020 in general, with a historic peak in 2011; 2) under the traditional trajectory, reaching the peak before 2030 is difficult; while under the carbon-neutral scenario, carbon peak will be achieved before 2025, and carbon neutrality can be achieved by 2050; 3) Great efforts are needed even in the process of peaking carbon emissions, especially in industrial sectors; 4) the integration of technology innovation and policy mechanisms is crucial to realizing zero carbon target. 5) This study provides improved understanding of urban carbon peaking and neutrality process from a systematic perspective, which could potentially help accelerate the sustainable transition towards carbon neutrality for cities that face dual challenges of development and decarbonization.

Keywords: carbon neutrality; sustainability; carbon emissions; energy transition; scenario analysis

NONMENCLATURE

Abbreviations	
IPAT	Impacts of population, affluence, and technology
STIRPAT	Stochastic impacts by regression on population, affluence and technology
LMDI	Logarithmic mean divisia index
SDGs	Sustainable Development Goals
CEADs	Carbon Emission Accounts and Datasets
Symbols	
%	ratio

1. INTRODUCTION

As the main carrier of global energy consumption and greenhouse gas emissions, cities are the key to realizing global carbon neutrality and sustainable development. Urban CO_2 emissions account for more than 70% of the global total [5] and are mainly driven by economic activities and social development [6-9]. To limit the global mean temperature rise to 1.5 ℃, global net anthropogenic CO_2 emissions need to achieve net-zero by 2050 [11, 12]. The Paris Agreement have put forward new expectations all countries, while some developed countries have already achieved peak of CO_2 emissions [13-15]. As of December 2021, more than 130 countries have announced their carbon neutrality goals [17], accounting for approximately 72% of the global greenhouse gas emissions [19]. Further, more than 500 cities have established low-carbon or net-zero carbon goals [20]. For instance, Tokyo has set the goal of carbon neutrality in 2050 and put forward various implementation plans and actions [21].

However, most developing countries are still struggling in the stage of urbanization and industrialization, hence their energy consumption and greenhouse gas emissions are expected to increase

This is a paper for Applied Energy Symposium 2023: Clean Energy towards Carbon Neutrality (CEN2023), April 23-25, 2023, Ningbo, China.

continuously [23]. At the same time, limited by domestic economic development and technological level, it is more difficult for cities in developing countries to peak carbon emissions and achieve net-zero carbon transition within a short period [26]. Furthermore, the profound changes in the external environment require more comprehensive and detailed CO_2 emission analysis and forecasting [27, 28]. For instance, the coronavirus disease (COVID-19) epidemic has had a huge impact on the global economy and social development, resulting in a decline in global CO_2 emissions in 2020. However, the economic recovery in the post-epidemic era may lead to a retaliatory rebound in CO_2 emissions [29], especially in developing countries.

In September 2020, Xi Jinping proposed that China will strive to peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060 [31], which set a rigid constraint for future carbon emissions. As the economic and financial center of China, Shanghai has a high-density population and high-intensity economic activities, which result in a high proportion of industrial, traffic, and building emissions [33]. Since 2011, the CO_2 emissions of Shanghai have gradually shown a trend of decoupling from economic development and energy consumption growth. However, high-carbon energy structure (e.g., coal, oil, and imported coal-fired power electricity) and the share of heavy industries remain relatively high. In addition, emissions from the transportation and building sectors are on the rise [32]. In the future, the improvement of urban functions and industrial development may further increase emissions [37].

Therefore, high-quality carbon peaking is an important goal for the development of Shanghai. However, the limited space for renewable energy development, limited potential for ecological carbon sink, and insufficient storage for low-carbon and carbon-negative technologies raise huge challenges for Shanghai. According to the the "Shanghai urban master plan (2017-2035), Shanghai will take the lead in exploring the path of carbon peaking, which can be a solid foundation for carbon neutrality and contribute to the sustainable transition of other similar cities and regions.

The remainder of this paper is structured as follows: Section 2 reviews available research on CO_2 emissions home and abroad. Section 3 provides methodology and data sources used in this study. Section 4 outlines the total energy consumption, energy structure, total CO_2 emissions and structure expected by 2050 under three scenarios. Section 5 proposes a framework of net zero carbon transition of cities and provides policy suggestions. Finally, Section 6 gives the conclusion.

2. LITERATURE REVIEW

Carbon neutrality roadmaps for cities in developing countries are completely different from those in developed countries due to historical, social, and economic limitations[39]. Specifically, how to achieve net-zero carbon transition in developing countries while maintaining economic growth is a challenging problem [40, 41]. Cities in developing countries usually face multiple socio-economic and environmental requirements [43], which need a cost-effective and acceptable roadmap to achieve sustainable carbon neutrality [45]. However, there are few benchmarks and successful models available for urban carbon neutrality of developing countries [48].

Many studies have developed various carbon emission analysis models and methods [49-52], such as the impacts of population, affluence, and technology (IPAT), stochastic impacts by regression on population, affluence and technology (STIRPAT), and logarithmic mean divisia index (LMDI) models as well as the KAYA identity. In 1971, the IPAT model was put forward by Ehrlich et al. [49]. The theoretical basis and expression of the IPAT model are relatively simple but it cannot reflect the mutual influence of population and economy, nor does it considers the difference between pollutant production and emissions [53]. Based on the IPAT model, Dietz et al. [50]established a STIRPAT regression model to estimate the population, economic development, and technological level; however, it did not solve the most prominent problems of the IPAT model. In 1990, Japanese professor Yoichi KAYA proposed the KAYA identity and established a corresponding relationship between greenhouse gas emissions and population, economic development level, energy utilization efficiency, and carbon emission factors through a factorization method [51]. In 2004, Ang proposed the LMDI model, used to decompose CO_2 emissions [54] and energy consumption [55], to analyze different contributions of the selected indicators. Because it has the advantage of no residual decomposition [56] and is universal [52], this model is widely applied in carbon emission decomposition studies.

The previous studies on CO_2 emissions estimation and driving forces analysis in some typical countries and cities are presented in Table 1. In terms of the methodology, models (such as the KAYA identity, LMDI model) and scenario analysis are commonly used. However, the carbon peaking and neutrality process and associated driving factors are still in debate. Consequently, the transition path to net-zero carbon development remains uncertain, especially for cities in

Tab. 1. Integrated analysis framework

Author	Period	Area	Methodology	Research content
Sikarwar et al. [1, 2]	2019-2020	Global	Modeling	Impact of the COVID-19 on carbon emissions and the economy
Jung et al. [3]	2015	U.S.	Analytical and statistical models	Impact of urban centers on traffic carbon emissions
Abe et al. [4]	2010-2018	Tokyo	Difference-in-differences (DID) estimation	Impact of the Tokyo emissions trading scheme on energy consumption and economic performance
Björkegren et al. [10]	2012-2013	London	The micrometeorological approach	Carbon emission accounting
Su et al. [16]	2000-2010	Singapore	Input-output and structural decomposition analysis	Input-output and structural decomposition analysis of carbon emissions
Wang et al. [18]	2012-2014	Germany	energy balance models	Energy consumption and carbon emission monitoring
Wang et al. [2]	1995-2014	Yangtze River Delta	Grey relational analysis	Impact of energy policy on energy-related CO_2 emissions
Li et al. [22]	2000-2009	Chongming	Greenhouse gas emission Inventory	Energy-related CO_2 emissions accounting
Li et al. [24]	1995-2020	Shanghai	Scenario analysis	Energy demand and energy-related CO_2 emission estimation and forecast
Guo et al. [25]	2005-2020	Shanghai	Scenario analysis, system analysis	A systematic approach to CO_2 emission reduction at city level
Wei et al. [30]	2007-2012	Shanghai	LMDI、SDA	CO_2 emissions from electricity
Luo et al. [32]	1995-2017	Shanghai	LMDI、granger causality test	Analysis of driving factors of urban CO_2 emissions
Liu et al. [34]	1970-2020	China	Literature review	Analysis of CO_2 emission drivers and the path to carbon neutrality
Rode et al. [35]	2000-2300	Earth	Data-driven spatial climate impact model	Social cost of energy-related CO_2 emissions
Helveston et al. [36]	2006-2018	China	Literature review	Promotion of low-carbon energy technologies
Ma et al. [38]	2000-2015	China	KAYA、LMDI	Analysis of the driving factors of CO_2 emissions from commercial buildings
Yang et al. [26]	1996-2016	China	KAYA、LMDI	Analysis of the driving factors of energy-related CO_2 emissions
Hu et al. [42]	1991-2016	Belt and Road countries	KAYA、LMDI、tapio decoupling model	Analysis of CO_2 emission driving factors and temporal and spatial evolution
Jiang et al. [44]	2007-2016	China	KAYA、LMDI	Analysis on influencing factors of non-residential electricity consumption
Xu et al. [46]	1995-2012	China	LMDI	Analysis of influencing factors of regional CO_2 emissions
Song et al. [47]	1995-2010	Yangtze River Delta	LMDI	Analysis of the driving factors of energy-related CO_2 emissions

developing countries with different historical, social, and economic situations.

3. METHODS

3.1 Integrated analysis framework

Different from previous approaches, this study introduces the impacts of the SDGs and COVID-19 when setting the parameters of different scenarios. Three scenarios are developed, including the frozen scenario (S1), low-carbon scenario (S2), and carbon-neutral scenario (S3). The three scenarios describe the change of carbon emissions under unregulated, regulated, and strongly regulated conditions, respectively.

Based on the data of the base year 2019, the forecast was made by adjusting various energy and industry parameters to simulate the changing energy consumption and carbon emissions in Shanghai between 2020 and 2050. In addition, the three scenarios share the same population, economic level, and total energy consumption.

The overall framework is shown in Figure 1.

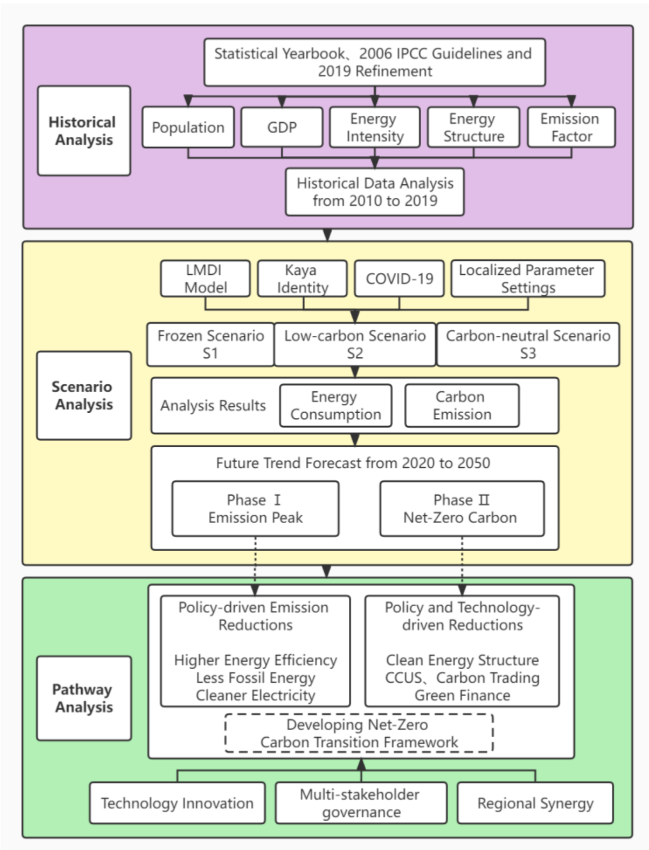

Fig. 1. Integrated analysis framework

3.2 Scenario Description

The three scenarios are described below:

3.2.1 Frozen Scenario (S1)

The previous economic and social growth model continues and the energy structure and electricity carbon emission coefficient remain unchanged since 2019. No policies and actions are implemented, such as industrial upgrading, energy transformation, technological progress, and emission reduction policies.

3.2.2 Low-carbon Scenario(S2)

According to the requirements for the energy structure adjustment in the current government plans and the expectation of technological progress, the energy structure of different sectors is adjusted accordingly. The main reference documents are the "Shanghai urban master plan (2017-2035)", the "Outline of the 13th Five-Year Plan for National Economic and Social Development of Shanghai", "Outline of the 14th Five-Year Plan for National Economic and Social Development of Shanghai and Vision 2035", other special plans for Shanghai and the "Key Work Arrangements for Energy Conservation, Emission Reduction and Climate Change in Shanghai" for each year since 2016.

3.2.3 Carbon-neutral Scenario(S3)

Under the premise of achieving a peak in carbon emissions by 2025 and net-zero carbon transition around 2050, the parameters and actions are further improved and enhanced based on the level of S2 and global trend.

3.3 KAYA-LMDI Model

According to KAYA-LMDI model, this study analyzes CO_2 emissions based on three factors, including activity level, energy intensity, and carbon emission factor. The LMDI method can fully factorize during analysis without leaving residuals [57]. Despite the limitations of zero and negative values, the probability of negative values is negligible as the data did not involve any such values [58]. There are two forms of LMDI models: additive and multiplicative decomposition, of which additive decomposition is the easier to use and explain [59]. The specific formula is as follows:

$$I = \sum_{i=1}^{n} P \times \left(\frac{GDP}{P}\right) \times \left(\frac{TCE}{GDP}\right) \times \left(\frac{TCE_i}{TCE}\right) \times \left(\frac{CO_{2i}}{TCE_i}\right)$$

$$\ln I_{CO2i} = \ln\mathrm{P} + \ln\left(\frac{GDP}{P}\right) + \ln\left(\frac{TCE}{GDP}\right) + \ln\left(\frac{TCE_i}{TCE}\right) + ln\left(\frac{CO_{2i}}{TCE_i}\right)$$

where I is the CO_2 emission, n is the number of energy sources, P is the population, TCE is the energy consumption, TCE_i is the energy consumption of energy type i, and CO_{2i} is the CO_2 emissions of energy type i.

With reference to the KAYA identity and LMDI model, the energy consumption and carbon emission estimation formulas are as follows:

$$T = \sum_{i=1}^{4} (Q_i \times E_i) = \sum_{i=1}^{7} A_i \times r_i$$

$$lnT_i = lnQ_i + lnE_i = lnA_i + lnr_i$$

where T is the total energy consumption (10^4 tce), Q_i is the GDP of each sector (100 million yuan) or the permanent population (10^4 people), $\mathrm{E_i}$ is the energy consumption per unit GDP of the sub-sector (tce/10^4 yuan) or the per capita annual energy consumption (tce/person), A_i is the consumption by energy type (ton), and r_i is the coefficient of converted standard coal, which differs for different energy types.

$$I = \sum_{i=1}^{4}(Q_i E_i \times \omega) = \sum_{i=1}^{7}(A_i r_i \times \omega_i)$$

$$lnI_i = lnQ_i + lnE_i + ln\omega = lnA_i + lnr_i + ln\omega$$

where I is the total amount of carbon emissions (t CO_2) and ω is the emission factor (t CO_2/tce), which refers to the CO_2 emission coefficient of various energy forms.

3.4 Data

In this study, the final energy consumption sectors include agriculture, industry, construction, transportation, terminal retail & other industries, and residences. The main energy sources are coal, oil, natural gas, heat, electricity and renewable energy. Both scope 1 and 2 emissions are included. The energy balance sheet and detailed energy consumption data for 2010-2019 are from the "China Energy Statistical Yearbook" and the "Shanghai Statistical Yearbook." In addition, the emission factors of various energy types were determined according to the latest guidelines and local information, including the "2006 IPCC Guidelines for National Greenhouse Gas Inventories" and the "2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories", the "Guidelines for the preparation of provincial carbon dioxide emission peaking action plan", the "Shanghai Greenhouse Gas Emissions Accounting and Reporting Guidelines (Trial)" issued by the Shanghai Municipal Development and Reform Commission in 2012, and local surveys on the government and academies.

4. RESULTS

4.1 Final Energy Consumption

The forecast of final energy consumption in Shanghai is shown in Figure 2. Between 2020 and 2050, the energy consumption demand in Shanghai will gradually increase, of which the industrial energy consumption will decrease while the tertiary industry and residential energy consumption will increase. At the same time, the energy consumption per unit of GDP decreases continuously, while the rate of decline gradually decreases, indicating that there is a "stuck neck" limitation in the field of core energy technologies. By 2035, the total energy consumption in Shanghai will increase to 133 million tce and the energy consumption per unit of GDP will drop to 0.184 tce/10^4 yuan, which is lower than the target of 0.22 tce/10^4 yuan in the 2035 plan. By 2050, the total energy consumption will increase to 155 million tce and the energy consumption per unit of GDP will be reduced by 63.00% compared with that of 2020.

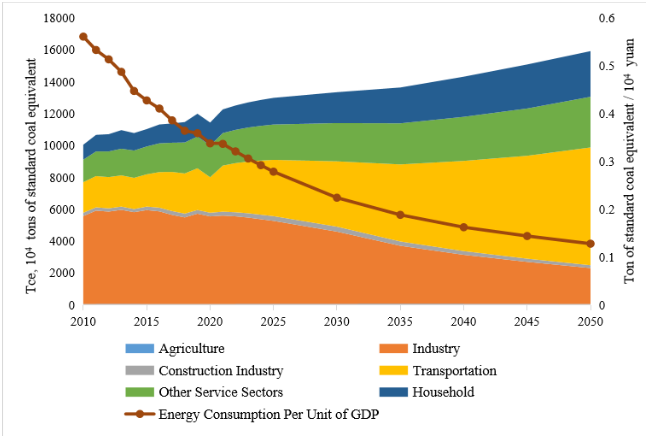

Fig. 2. Final Energy Consumption Forecast

If the energy structure and industrial structure in 2019 are not changed, CO_2 emissions in Shanghai will continue to increase, making carbon peaking and carbon neutrality goals difficult to achieve. Aiming to provide a possible path towards carbon neutrality, the study focuses on the analysis of energy consumption and carbon emissions in the low-carbon scenario and the carbon-neutral scenario.

4.2 Energy Structure

The forecast of the energy structure in Shanghai is shown in Figure 3. There are differences in the energy structure of S2 and S3 but the development trend is the same. Fossil energy is gradually declining in primary industry, being replaced by electricity, hydrogen energy, and biodiesel. Natural gas will become an important transitional energy source for industries. Electricity will become the main energy source almost in every final sector and the proportion of hydrogen energy and biodiesel will increase. The improvement of the aviation energy structure will become the key to energy conservation and emission reduction in the transportation sector[60, 61]. In the 2040–2050 period under carbon-neutral scenario, no fossil energy will be used except for jet fuel.

4.3 Total CO_2 Emissions

Based on the energy demand, energy structure and carbon emission factors, the energy-related carbon emission trajectories were simulated, as shown in Figure 4. Except the frozen scenario, the total CO_2 emissions in Shanghai decreased gradually since 2011, although in some years the emissions fluctuated.

Under the frozen scenario, the CO_2 emissions in

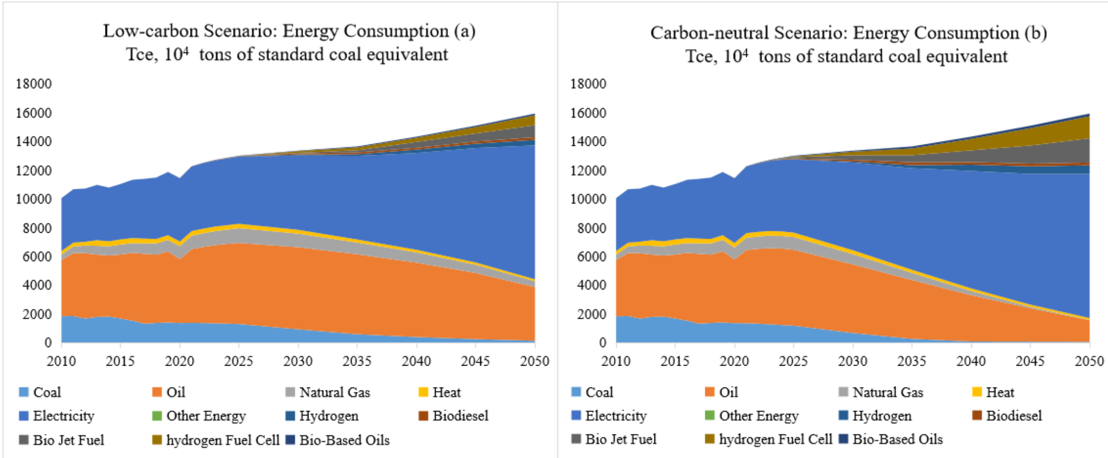

Fig. 3. Energy structure change under (a) low-carbon scenario and (b) carbon-neutral scenario

Shanghai will continue to increase, hence CO_2 peaking cannot be achieved.

Under the low-carbon scenario, technological progress and energy transition can effectively slow down the increase in carbon emissions. The CO_2 emissions will peak in 2025 with 218 million tons and total CO_2 emissions will be reduced to 10^9 million tons by 2050.

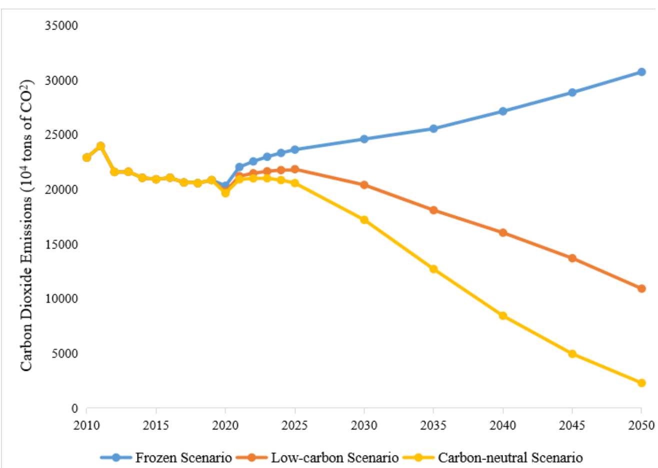

Fig. 4. CO_2 emission change for frozen, low-carbon, and carbon-neutral scenarios

Under the carbon-neutral scenario, the CO_2 emissions will peak in 2023 with 210 million tons CO_2. By 2050, Shanghai will achieve zero carbonization of electricity with aviation fuel emissions being the only source of emissions. In addition, the total CO_2 emissions will be reduced to 23 million tons in 2050, the CO_2 emissions per unit of GDP will be reduced to 0.02 tons $CO_2/10^4$ yuan, and the per capita CO_2 emissions will be reduced to 0.92 tons CO_2/(person·year). Compared with the frozen and low-carbon scenarios, the carbon-neutral scenario has a lower total carbon emission. However, Shanghai has limited ecological endowments and insufficient ecological carbon sink potential. It is therefore necessary to comprehensively consider the development of carbon capture, utilization, and storage (CCUS) technology, the carbon trading market, and other means to achieve net-zero carbon target.

4.4 CO_2 Emissions Structure

By analyzing the industrial and energy breakdowns of carbon emissions, the key sectors and main energy types for net-zero carbon transition were identified (figure 5).

Between 2019 and 2050, the contribution of emission reduction for each industry was estimated as follows: agriculture (0.63%), industry (47.48%), construction industry (2.62%), transportation (17.14%), other service sectors (19.67%), and household (12.47%). Energy conservation and emission reduction in the industry, transportation, and other service sectors are key sectors to promote the net-zero carbon transition. The energy consumption of agriculture, industry, construction, other service sectors, and household in 2050 will account for more than 50%; however, these sectors' carbon emissions will drop to zero, indicating that under the carbon-neutral scenario, all industries except transportation will achieve zero emissions. The main carbon emission in the transportation sector comes from aviation kerosene and the realization of net-zero carbon transition urgently requires breakthroughs in aviation fuel technologies.

Between 2019 and 2050, the emission reduction contributions of various energy sources were estimated as follows: coal products (14.96%), oil products (32.38%), natural gas (6.82%), heat (4.79%), and electricity (41.05%). Currently, coal and oil products are still the main sources of CO_2 emissions in secondary energy consumption, accounting for nearly 60% of the total emissions. Under the carbon-neutral scenario, emissions from coal will continue to decrease, while oil and natural gas emissions will peak in 2024 and 2025 and then decline. By 2050, the main energy sources will be electricity, oil products, hydrogen and biodiesel. The energy structure should be improved by strengthening the aviation fuel substitution, banning the sale of fuel vehicles, and providing clean energy alternatives.

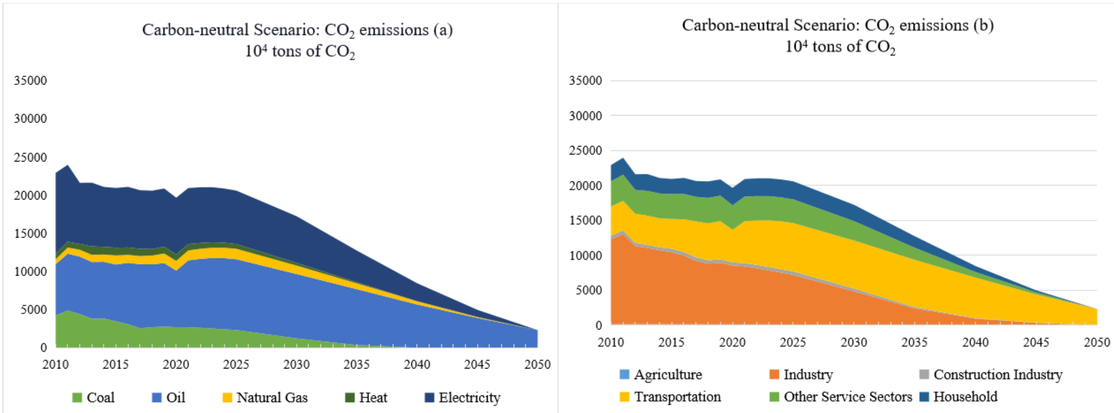

Fig. 5. CO_2 emission structure change under carbon-neutral scenario

In addition, promoting full electrification and zero carbonization of electricity is the fundamental path to achieve net-zero carbon transition. Under the carbon-neutral scenario, the fossil energy is gradually replaced by electricity and the emission factor of electricity continues to decline with a zero carbonization of electricity by 2050, which will play an important role in the process of decarbonization.

5. DISCUSSION

5.1 Key factors on carbon emissions reduction

An accurate understanding of the key factors affecting carbon emissions is the basis for a successful transition. Based on the KAYA-LMDI, we carried out a long-term carbon emission forecast of Shanghai under the influence of multiple factors, such as carbon neutrality constraint, energy structure adjustment and the impact of the new crown pneumonia epidemic.

From a historical perspective, three factors play important roles on the 2010-2019 change of carbon emissions in Shanghai, including economy, energy intensity and emission factors (Figure 6). This result is consistent with the findings of previous studies[62-64] and provides a refined analysis at local level. In particular, the decline of energy intensity and emission factors played a continuous positive role in reducing carbon emissions. It is worth mentioning that in 2012, the sharp decline in emission factors made an important contribution to the reduction in CO_2 emissions. This is probably due to the large amount of historical works done during and before the 11th Five-Year Plan period. These works include efforts to improve the energy efficiency of coal-fired power generation and introduction of external green power, resulting in a significant decrease in electricity emission factors in Shanghai during the 12th Five-Year Plan period [30]. However, as the economic center of China and leader of the Yangtze River Economic Belt in China, the high-intensity economic activities in Shanghai have played a great role in promoting the increase in its CO_2 emissions [65].

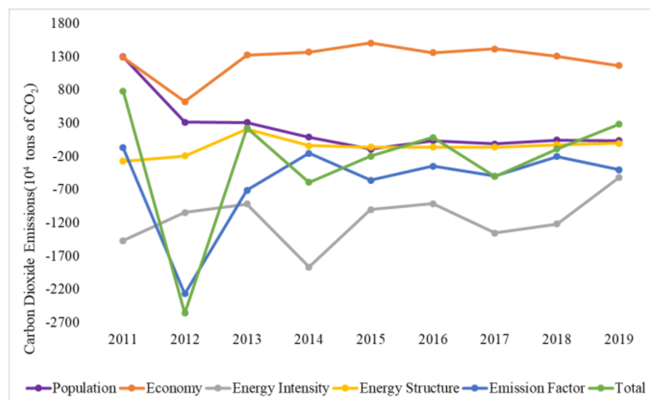

Fig. 6. Contributions of multiple factors on carbon emissions (2010–2019)

From 2020 to 2035, economic growth is still the most influencing factors on carbon emissions. Energy intensity and emission factor also play positive roles in carbon emission reduction. The results in Figure 7 indicate that the energy efficiency management measures before 2035 have a significant effect on the reduction of carbon emissions under S3, laying the solid foundation for the future net-zero carbon transformation.

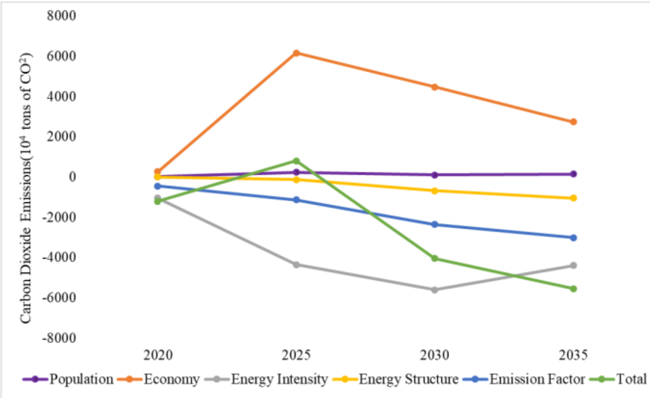

Fig. 7. Contributions of multiple factors on carbon emissions under S3(2020–2035)

After 2035 [1], carbon reduction in Shanghai was mainly attributed to the reduction in emission factors, ecological carbon sinks and innovative carbon mechanisms. Energy technology innovation and tailored low carbon policies can help Shanghai achieve zero carbon neutrality at a relatively low cost. And kerosene for aviation will be the major source of carbon emissions in 2050.

5.2 A technology-policy framework for decarbonization transition of cities in developing countries

Cities in developing countries cannot achieve carbon neutrality by following the same path as those in developed countries because they are different in institutional arrangement, policy environment and social acceptance. Most developed countries have already achieved carbon peaking and only need to consider carbon neutrality. For instance, the UK [66] and US [67] achieved peak carbon in 1991 and 2007, respectively. At the same time, developed cities attach more importance to environmental protection under the premise of better economic level and usually have advances in energy and resource technology. For example, Tokyo concentrates on breakthroughs in hydrogen energy technology [68] and Copenhagen owns resource endowment advantages [69].

However, determining an appropriate way to reduce CO_2 emissions on the premise of ensuring economic growth is a huge challenge for cities in developing countries [70]. Unlike the net-zero carbon transition paths of many developed countries, this study starts from the basic requirements of cities in developing countries to achieve carbon peaking and carbon neutrality through synergistic cooperation. The strategy of "Scheduled high-quality peaking and Technology-driven neutrality" is put forward, which emphasizes that carbon peaking and neutrality should be scientifically planned with different priorities for different sectors or areas from a holistic perspective. In addition, the reduction of carbon emission intensity should be paid more attention in short-term. The synergies and trade-offs among economic development, emission reduction and sink increase should be considered simultaneously. Therefore, in order to provide a clearer understanding on carbon neutrality transition for cities in developing countries, this study puts forward an integrated technology-policy

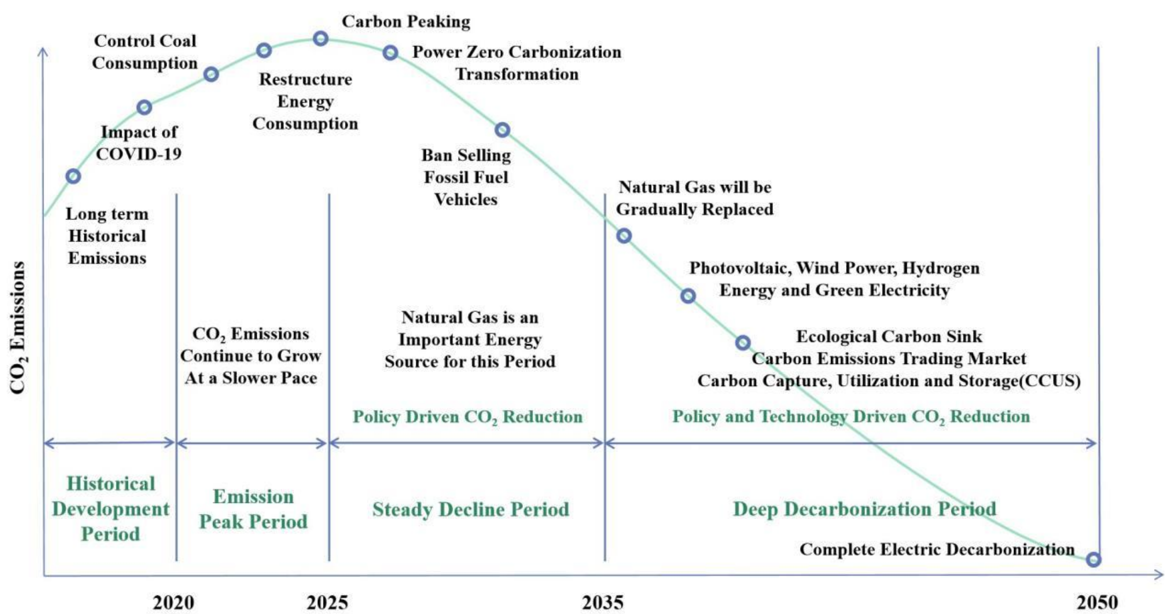

Fig. 8. Net-Zero Carbon Transition Framework

[1] The LMDI method requires non-zero variables. Therefore, the contributions of multiple variables can only be decomposed until 2035 since several variables will be zero after 2035.

framework of urban net-zero carbon transition (figure 8).

Figure 8 shows the CO_2 emission trajectory of developing countries under the carbon neutrality transition framework. However, due to the rapid economic development, the developing countries still needs to work hard on achieving the net-zero carbon emission by 2050. According to the current situation, carbon peaking is a policy focus at present and carbon neutrality is a long-term goal, which depends on the dual drive of technological innovation and policy innovation.

From 2020 to 2035, CO_2 emissions will experience a peak plateau and steadily decline, mainly driven by policy. Policy measures include the implementation of total coal consumption control and full substitution of gasoline and diesel through structural adjustments of energy consumption at the consumer end. At the same time, the comprehensive electrification and zero-carbon transformation of electricity is promoted to achieve a "less coal and low oil" pattern of final energy consumption by 2025. From 2025 to 2035, the banning of fossil fuel vehicles sale will be gradually implemented and fossil fuel vehicles will be replaced by new energy vehicles step by step. During this period, natural gas, as an important energy source in the transition period, will significantly increase its supply, storage, and usage [71].

From 2035 to 2050, the developing countries will enter a period of deep decarbonization. The importance of policy innovation in driving a low-carbon urban transition has been demonstrated [72]. Carbon neutralization will be achieved at this stage through a two-wheel drive mechanism of policy and technology. Natural gas will be gradually replaced by cleaner energy forms, such as photovoltaics, wind power, hydrogen energy and external green power. At the same time, the carbon emission factor of electricity will continue to decline and the zero carbonization of electricity will be achieved by 2050 [73]. By 2040, fuel vehicles are expected to be completely phased out. Between 2040 and 2050, kerosene consumption in the aviation industry will become the main source of carbon dioxide emissions. In 2050, there will still be some carbon emissions and the focus should center on the replacement of aviation kerosene and transformation of aviation engine efficiency. At the same time, neutralization is achieved through using natural carbon sinks, CCUS technology, and carbon emissions trading mechanism.

5.3 Policy implications

As the economic center of China, Shanghai offers multiple advantages and a pivotal strategic position. Therefore, Shanghai should take a leading role in achieving carbon neutrality. Based on the above findings, this study suggests that Shanghai should try to achieve the target of carbon neutrality by 2050. It is worth highlighting that Shanghai could achieve final net-zero carbon not by only relying on its own smaller carbon sinks but on its technological innovations and the surrounding resources, such as the renewable and clean power grid of the Yangtze River Delta region. In addition, as Shanghai is also the financial center of China, the economic instruments such as green finance and carbon trading market will also play an important role. The carbon neutrality in Shanghai is also conductive to its role as a leader in East China and the Yangtze River Basin, providing a benchmark and model for other cities through regional cooperation and integration.

The following policy recommendations are suggested based on the previous analysis. In terms of energy, the consumption of coal and oil products should be strictly controlled and the development of new energy sources, such as solar, wind power, hydrogen and biomass energy, should be further promoted. Distributed energy storage, distributed photovoltaic, and the associated equipment construction and power supply guarantee capabilities should be strengthened. In terms of technology, a long-term roadmap for local development of carbon neutral technology should be developed as soon as possible. Breakthrough energy technologies and negative carbon technologies such as hydrogen fuel cells, bio-based fuels and CCUS technologies should be explored according to local conditions. Clean energy and low-carbon technological innovation should be continuously promoted and energy-saving and low-carbon industrial parks could be established to demonstrate advanced carbon neutral technologies. In terms of policies and systems, the cultivation and expansion of the green and low-carbon financial market should be further enhanced, such as the promotion of green financial products such as green bonds, green insurance, and green funds[74]. Relying on the deep integration of digital technology and carbon finance, carbon inclusiveness mechanism should be developed and closely connected to the existing national and local carbon trading markets. The effective cooperation of multiple stakeholders such as government, enterprises, think tanks, NGOs and the public should also be improved.

Finally, different stakeholders could play diverse roles in achieving carbon neutrality. For instance, the government could promote the legislation of carbon neutrality and the improvement of associated standards. And the enterprises could play a major role in integrating carbon neutral targets into their main business and long-term development strategies, promoting the green and low-carbon transformation of themselves and their upstream and downstream supply chains. As the ultimate beneficiaries of green and low-carbon development, the public is encouraged to adopt green and low-carbon lifestyles, which can provide the core driving force for carbon neutrality transition.

5.4 Uncertainties and Limitations

Regarding the methodology, the research was based on the KAYA identity and LMDI model, which has the advantages of simple mathematical form, strong data availability, and strong explanatory power for the driving factors of carbon emission changes. However, it may ignore potential complex connections between social-economic development and ecological constraints under the goal of carbon neutrality, which can be further improved in future research. In addition, in late 2022, China further optimized the measures to prevent and control COVID-19. The accelerated economic recovery and the restart of large-scale resumption of work and production in Shanghai still leave a large uncertainty in the impact on carbon emissions.

Due to data availability, this study only calculated energy-related carbon emissions, which accounts for a large proportion of the total carbon emissions in Shanghai. Non-energy processes and carbon emissions from greenhouse gases other than CO_2, such as land use or agricultural fertilizer use, were not considered. In terms of data accuracy, since the energy balance sheet in the Shanghai Statistical Yearbook lacks the final energy consumption classified by energy type, this study used the Shanghai Energy Balance Sheet (physical quantity) data in the China Energy Statistical Yearbook as a substitute. Its statistical caliber may be different from that in Shanghai, which will have a certain impact on the research results.

In order to verify the accuracy of the carbon emission accounting method used in this study, we also compare the CO_2 emissions results with the data from the Carbon Emission Accounts and Datasets (CEADs). Taking the year of 2019 as an example, the total energy-related carbon emissions of Shanghai in this study are 209 Mt, higher than the result of CEADs (193 Mt). We found that the differences come from two aspects. One is the different accounting scope, this study calculates the carbon emissions of Shanghai from scope 1 and scope 2, while the result of CEADs only includes the carbon emissions of scope 1 (The carbon emissions of scope 2 are mainly caused by the net transfer of electricity from other provinces and cities to Shanghai). According to our estimation, the scope 2 emission of Shanghai in 2019 is about 36 Mt, indicating that the scope 1 emission in this study is lower than that in CEADs. Secondly, the emission factors are different, as CEADs use the emission factor of the whole China through a large-scale survey of Chinese coal mines. In this study, local carbon emission factors were adopted to provide a relatively more refined and accurate emission baseline.

6. CONCLUSIONS

The consequences of global climate change are of great concern and achieving net-zero carbon emission by 2050 seems like a difficult task. Most developed countries have achieved a smooth transition from carbon peaking to carbon neutrality. However, the carbon emission trajectories of developing countries are quite different as their resources and capabilities for emission reduction are still very limited. Considering the key requirements of balancing economic growth and carbon neutrality in developing countries, this study proposes a new framework for analyzing carbon peaking and neutrality process holistically by integrating the KAYA-LMDI and scenario analysis approach. Three scenarios are developed to analyze and predict the energy-related carbon emissions between 2010 and 2050, taking Shanghai as a case.

The results show that the sustainability of the current energy structure and development model in Shanghai is facing huge challenges, resulting in difficulties in achieving net-zero carbon target. Shanghai should promote the green transformation of industrial sectors by enhancing stock optimization and incremental upgrading, develop advanced new energy and negative carbon technology, and establish innovative and flexible policy support system. In particular, carbon market and associated green finance innovations are crucial to achieving carbon neutrality at low cost and high efficiency. A policy- and- technology-driven net-zero carbon transition pathway is also developed, which provides the foundation for achieving carbon peaking and carbon neutrality. In addition, the implementation of carbon-neutral target requires strong policy support from the effective cooperation of multiple stakeholders such as government, enterprises, think tanks, NGOs and the public. Aiming to provide a sustainable pathway to achieve net-zero carbon transition, this study provides improved understanding of urban carbon peaking and neutrality process for cities in developing countries, which could potentially help accelerate the sustainable transition towards carbon neutrality for cities that face dual challenges of socio-economic development and deep decarbonization.

ACKNOWLEDGEMENT

This research is supported by Chinese National Natural Science Foundation (42071293); Many appreciations for the support from the Fundamental Research Funds for the Central Universities; Many appreciations for the support from the Key Laboratory of Cities Mitigation and Adaptation to Climate Change in Shanghai. The authors would like to express their gratitude to Angzu Cai and Leyi Wang for assistance with this paper.

DECLARATION OF INTEREST STATEMENT

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. All authors read and approved the final manuscript.

REFERENCE

[1] Sikarwar VS, Reichert A, Jeremias M, Manovic V. COVID-19 pandemic and global carbon dioxide emissions: A first assessment. Science of The Total Environment. 2021;794:148770.

[2] Wang L, Gong Z, Gao G, Wang C. Can energy policies affect the cycle of carbon emissions? Case study on the energy consumption of industrial terminals in Shanghai, Jiangsu and Zhejiang. Ecological Indicators. 2017;83:1-12.

[3] Jung MC, Kang M, Kim S. Does polycentric development produce less transportation carbon emissions? Evidence from urban form identified by night-time lights across US metropolitan areas. Urban Climate. 2022;44:101223.

[4] Abe T, Arimura TH. Causal effects of the Tokyo emissions trading scheme on energy consumption and economic performance. Energy Policy. 2022;168:113151.

[5] Gurney KR, Liang J, Roest G, Song Y, Mueller K, Lauvaux T. Under-reporting of greenhouse gas emissions in U.S. cities. Nature Communications. 2021;12:553.

[6] Wu Y, Tam VWY, Shuai C, Shen L, Zhang Y, Liao S. Decoupling China's economic growth from carbon emissions: Empirical studies from 30 Chinese provinces (2001–2015). Science of The Total Environment. 2019;656:576-88.

[7] Dong F, Li J, Wang Y, Zhang X, Zhang S. Drivers of the decoupling indicator between the economic growth and energy-related CO_2 in China: A revisit from the perspectives of decomposition and spatiotemporal heterogeneity. Science of The Total Environment. 2019;692:631-58.

[8] Wang Q, Zhao M, Li R, Su M. Decomposition and decoupling analysis of carbon emissions from economic growth: A comparative study of China and the United States. Journal of Cleaner Production. 2018;197:178-84.

[9] Mma B, Wei CC, Wca B, Liang D. Whether carbon intensity in the commercial building sector decouples from economic development in the service industry? Empirical evidence from the top five urban agglomerations in China. Journal of Cleaner Production. 2019;222:193-205.

[10] Björkegren A, Grimmond CSB. Net carbon dioxide emissions from central London. Urban Climate. 2018;23:131-58.

[11] IPCC. Special report on global warming of 1.5℃. 2018.

[12] Dong H, Fujita T, Geng Y, Dong L, Ohnishi S, Sun L, et al. A review on eco-city evaluation methods and highlights for integration. Ecological Indicators. 2016;60:1184-91.

[13] Waheed R, Sarwar S, Chen W. The survey of economic growth, energy consumption and carbon emission. Energy Reports. 2019;5:1103-15.

[14] Saidi K, Mbarek MB. Nuclear energy, renewable energy, CO_2 emissions, and economic growth for nine developed countries: Evidence from panel Granger causality tests. Progress in Nuclear Energy. 2016;88:364-74.

[15] Cai Y, Sam CY, Chang T. Nexus between clean energy consumption, economic growth and CO_2 emissions. Journal of Cleaner Production. 2018;182:1001-11.

[16] Su B, Ang BW, Li Y. Input-output and structural decomposition analysis of Singapore's carbon emissions. Energy Policy. 2017;105:484-92.

[17] Höhne N, Gidden MJ, den Elzen M, Hans F, Fyson C, Geiges A, et al. Wave of net zero emission targets opens window to meeting the Paris Agreement. Nature Climate Change. 2021;11:820-2.

[18] Wang Y, Du J, Kuckelkorn JM, Kirschbaum A, Gu X, Li D. Identifying the feasibility of establishing a passive house school in central Europe: An energy performance and carbon emissions monitoring study in Germany. Renewable and Sustainable Energy Reviews. 2019;113:109256.

[19] Olivier J, Schure KM, Peters J. Trends in global CO_2 and total greenhouse gas emissions: 2019 report.

[20] Ramaswami A, Tong K, Canadell JG, Jackson RB, Stokes E, Dhakal S, et al. Carbon analytics for net-zero

emissions sustainable cities. Nature Sustainability. 2021;4:460-3.
[21] Tokyo Metropolitan Government. Zero Emission Tokyo: A Sustainability and Resilience Strategy Pursuing 1.5ºC. 2019.
[22] Li Q, Guo R, Li F, Xia B. Integrated inventory-based carbon accounting for energy-induced emissions in Chongming eco-island of Shanghai, China. Energy Policy. 2012;49:173-81.
[23] De La Peña L, Guo R, Cao X, Ni X, Zhang W. Accelerating the energy transition to achieve carbon neutrality. Resources, Conservation and Recycling. 2022;177:105957.
[24] Li L, Chen C, Xie S, Huang C, Cheng Z, Wang H, et al. Energy demand and carbon emissions under different development scenarios for Shanghai, China. Energy Policy. 2010;38:4797-807.
[25] Guo R, Cao X, Yang X, Li Y, Jiang D, Li F. The strategy of energy-related carbon emission reduction in Shanghai. Energy Policy. 2010;38:633-8.
[26] Yang J, Cai W, Ma M, Li L, Liu C, Ma X, et al. Driving forces of China's CO_2 emissions from energy consumption based on Kaya-LMDI methods. Science of The Total Environment. 2020;711:134569.
[27] Guo R, Zhao Y, Shi Y, Li F, Hu J, Yang H. Low carbon development and local sustainability from a carbon balance perspective. Resources, Conservation and Recycling. 2017;122:270-9.
[28] Apergis N, Gupta R, Lau CKM, Mukherjee Z. U.S. state-level carbon dioxide emissions: Does it affect health care expenditure? Renewable and Sustainable Energy Reviews. 2018;91:521-30.
[29] Wang Q, Wang S. Preventing carbon emission retaliatory rebound post-COVID-19 requires expanding free trade and improving energy efficiency. Science of The Total Environment. 2020;746:141158.
[30] Wei W, Zhang P, Yao M, Xue M, Miao J, Liu B, et al. Multi-scope electricity-related carbon emissions accounting: A case study of Shanghai. Journal of Cleaner Production. 2020;252:119789.
[31] China Today. China and the UN: Working Together for Peaceful Development and Cooperation. 2020.
[32] Luo Y, Zeng W, Hu X, Yang H, Shao L. Coupling the driving forces of urban CO_2 emission in Shanghai with logarithmic mean Divisia index method and Granger causality inference. Journal of Cleaner Production. 2021;298:126843.
[33] Duan H, Zhou S, Jiang K, Bertram C, Harmsen M, Kriegler E, et al. Assessing China's efforts to pursue the 1.5°C warming limit. Science. 2021;372:378.
[34] Liu Z, Deng Z, He G, Wang H, Zhang X, Lin J, et al. Challenges and opportunities for carbon neutrality in China. Nature Reviews Earth & Environment. 2021.
[35] Rode A, Carleton T, Delgado M, Greenstone M, Houser T, Hsiang S, et al. Estimating a social cost of carbon for global energy consumption. Nature. 2021;598:308-14.
[36] Helveston J, Nahm J. China's key role in scaling low-carbon energy technologies. Science. 2019;366:794-6.
[37] Bodin Ö. Collaborative environmental governance: Achieving collective action in social-ecological systems. Science. 2017;357:eaan1114.
[38] Ma M, Cai W, Cai W. Carbon abatement in China's commercial building sector: A bottom-up measurement model based on Kaya-LMDI methods. Energy. 2018;165:350-68.
[39] Apergis N, Christou C, Gupta R. Are there Environmental Kuznets Curves for US state-level CO_2 emissions? Renewable and Sustainable Energy Reviews. 2017;69:551-8.
[40] Zhang C, Su B, Zhou K, Yang S. Decomposition analysis of China's CO_2 emissions (2000–2016) and scenario analysis of its carbon intensity targets in 2020 and 2030. Science of The Total Environment. 2019;668:432-42.
[41] Mariyam S, Shahbaz M, Al-Ansari T, Mackey HR, McKay G. A critical review on co-gasification and co-pyrolysis for gas production. Renewable and Sustainable Energy Reviews. 2022;161:112349.
[42] Hu M, Li R, You W, Liu Y, Lee C-C. Spatiotemporal evolution of decoupling and driving forces of CO_2 emissions on economic growth along the Belt and Road. Journal of Cleaner Production. 2020;277:123272.
[43] Guo R, Lv S, Liao T, Xi F, Zhang J, Zuo X, et al. Classifying green technologies for sustainable innovation and investment. Resources, Conservation and Recycling. 2020;153:104580.
[44] Jiang S, Zhu Y, He G, Wang Q, Lu Y. Factors influencing China's non-residential power consumption: Estimation using the Kaya–LMDI methods. Energy. 2020;201:117719.
[45] Bolea L, Duarte R, Sánchez-Chóliz J. Exploring carbon emissions and international inequality in a globalized world: A multiregional-multisectoral perspective. Resources, Conservation and Recycling. 2020;152:104516.
[46] Xu SC, He ZX, Long RY, Chen H, Han HM, Zhang WW. Comparative analysis of the regional contributions to carbon emissions in China. Journal of Cleaner Production. 2016;127:406-17.

[47] Song M, Guo X, Wu K, Wang G. Driving effect analysis of energy-consumption carbon emissions in the Yangtze River Delta region. Journal of Cleaner Production. 2015;103:620-8.
[48] Zhang R, Hanaoka T. Deployment of electric vehicles in China to meet the carbon neutral target by 2060: Provincial disparities in energy systems, CO_2 emissions, and cost effectiveness. Resources, Conservation and Recycling. 2021;170:105622.
[49] Ehrlich PR, Holdren JP. Impact of Population Growth. Science. 1971;171:1212-7.
[50] Dietz T, Rosa EA. Effects of population and affluence on CO_2 emissions. Proceedings of the National Academy of Sciences of the United States of America. 1997;94:175-9.
[51] Houghton RA, Nassikas AA. Global and regional fluxes of carbon from land use and land cover change 1850-2015. Global Biogeochemical Cycles. 2017;31:456-72.
[52] Ang BW. Decomposition analysis for policymaking in energy:: which is the preferred method? Energy Policy. 2004;32:1131-9.
[53] Candadai M, Setzler M, Izquierdo EJ, Froese T. Embodied Dyadic Interaction Increases Complexity of Neural Dynamics: A Minimal Agent-Based Simulation Model. Front Psychol. 2019;10:540.
[54] Cq A, Xc B, Sy C, Xin YA. Analysis on the influencing factors of carbon emission in China's logistics industry based on LMDI method - ScienceDirect. Science of The Total Environment. 2020;734.
[55] Wang, Miao, Feng, Chao. Decomposing the change in energy consumption in China's nonferrous metal industry: An empirical analysis based on the LMDI method. Renewable & sustainable energy reviews. 2018.
[56] Layzell, David B, Torrie, Ralph D, Stone, Christopher. Understanding energy systems change in Canada: 1. Decomposition of total energy intensity. Energy economics. 2016.
[57] Wang K, Wu M, Sun Y, Shi X, Sun A, Zhang P. Resource abundance, industrial structure, and regional carbon emissions efficiency in China. Resources Policy. 2019;60:203-14.
[58] Hang Y, Wang Q, Zhou D, Zhang L. Factors influencing the progress in decoupling economic growth from carbon dioxide emissions in China’s manufacturing industry. Resources, Conservation and Recycling. 2019;146:77-88.
[59] Zhao X, Zhang X, Shao S. Decoupling CO_2 emissions and industrial growth in China over 1993–2013: The role of investment. Energy Economics. 2016;60:275-92.
[60] ICAO. On Board A Sustainable Future. 2016.
[61] WRI. Research on the peak path of traffic carbon emissions in Wuhan. 2019.
[62] Liu G, Hao Y, Zhou Y, Yang Z, Zhang Y, Su M. China's low-carbon industrial transformation assessment based on Logarithmic Mean Divisia Index model. Resources, Conservation and Recycling. 2016;108:156-70.
[63] Kang Y, Yang Q, Wang L, Chen Y, Lin G, Huang J, et al. China's changing city-level greenhouse gas emissions from municipal solid waste treatment and driving factors. Resources, Conservation and Recycling. 2022;180:106168.
[64] Mohmmed A, Li Z, Olushola Arowolo A, Su H, Deng X, Najmuddin O, et al. Driving factors of CO_2 emissions and nexus with economic growth, development and human health in the Top Ten emitting countries. Resources, Conservation and Recycling. 2019;148:157-69.
[65] Zhao X, Ma X, Chen B, Shang Y, Song M. Challenges toward carbon neutrality in China: Strategies and countermeasures. Resources, Conservation and Recycling. 2022;176:105959.
[66] Leroutier M. Carbon pricing and power sector decarbonization: Evidence from the UK. Journal of Environmental Economics and Management. 2022;111:102580.
[67] Shao X, Zhong Y, Li Y, Altuntaş M. Does environmental and renewable energy R&D help to achieve carbon neutrality target? A case of the US economy. Journal of Environmental Management. 2021;296:113229.
[68] Li J, Meng G, Li C, Du K. Tracking carbon intensity changes between China and Japan: Based on the decomposition technique. Journal of Cleaner Production. 2022;349:131090.
[69] van Doren D, Driessen PPJ, Runhaar HAC, Giezen M. Learning within local government to promote the scaling-up of low-carbon initiatives: A case study in the City of Copenhagen. Energy Policy. 2020;136:111030.
[70] Goldemberg J. The evolution of the energy and carbon intensities of developing countries. Energy Policy. 2020;137:111060.
[71] Dong K, Sun R, Li H, Liao H. Does natural gas consumption mitigate CO_2 emissions: Testing the environmental Kuznets curve hypothesis for 14 Asia-Pacific countries. Renewable and Sustainable Energy Reviews. 2018;94:419-29.
[72] Luo Y, Zeng W, Wang Y, Li D, Hu X, Zhang H. A hybrid approach for examining the drivers of energy consumption in Shanghai. Renewable and Sustainable Energy Reviews. 2021;151:111571.

[73] Bonsu NO. Towards a circular and low-carbon economy: Insights from the transitioning to electric vehicles and net zero economy. Journal of Cleaner Production. 2020;256:120659.
[74] Dong K, Taghizadeh-Hesary F, Zhao J. How inclusive financial development eradicates energy poverty in China? The role of technological innovation. Energy Economics. 2022;109:106007.