博 士 学 位 論 文

Doctoral Dissertation

Synergy of Energy Poverty Alleviation and

Climate Change Mitigation in China

（中国におけるエネルギー貧困緩和と気候変動緩和のシナジー）

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Abstract

Climate change and poverty are interconnected problems that pose significant threats to the sustainable development of human society today. One manifestation of poverty is energy poverty, which greatly impacts population health, quality of life, socio-economic development, and equity. China, as the world's largest emitter of carbon, is taking responsibility by implementing a national strategy to address climate change, prioritizing carbon peaking and carbon neutrality. Simultaneously, as the world's largest developing country, China is making strides in alleviating economic poverty, but the rapid growth in residential energy consumption remains a challenge. While electricity access has been extended to all residents, the low level of energy consumption and poor energy consumption structure exacerbate the issue of energy poverty. Studies have indicated that increasing residential energy consumption leads to higher carbon emissions, although some suggest that long-term policy goals can align.

This study establishes a comprehensive index system consisting of 19 indicators to measure the level of energy poverty across 30 provinces of China. It also analyzes the carbon emissions resulting from residential energy consumption. Findings reveal an overall decline in energy poverty in recent years, but rural areas continue to face higher levels of energy deprivation compared to urban areas. Moreover, significant disparities exist between provinces, with variations in the pace of energy poverty alleviation and core issues surrounding it. The energy poverty index demonstrates a negative correlation with residents' carbon emissions.

Additionally, three scenarios with different energy structures — Business as Usual (BAU), Carbon Emission Reduction (CER), and Renewable Energy (REN) — were created to analyze changes in the energy poverty index and carbon emissions. Comparison among these scenarios reveals that, in the BAU scenario, the energy poverty index continues to decline while carbon emissions increase annually, consistent with historical data. Under the CER scenario, both the energy poverty index and

residential carbon emissions exhibit a decreasing trend, while the most significant decreases in both are observed in the REN scenario.

Furthermore, discussions encompass employment, economic aspects, and energy efficiency. The study proposes several policy recommendations, including expanding rural energy solutions and supporting clean energy, promoting energy efficiency, emphasizing employment during the transition period, and encouraging innovative financial and pricing policies. These findings and recommendations can help guide China in achieving its future goals of reducing energy poverty and reaching carbon emission reduction goals.

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Chapter 1. Introduction

The relationship between energy, development, and climate change is bidirectional. Energy poverty, as one of the manifestations of poverty, has a profound impact on the well-being of residents, socio-economic progress, and the establishment of an equitable society. The United Nations has recognized 'No poverty' and 'Affordable and clean energy' as sustainable development goals (SDGs) for 2030. Increased energy consumption drives productivity, economic growth, and improves individuals' quality of life. However, this also leads to higher greenhouse gas emissions, exacerbating climate change, with the poor being the most vulnerable to its effects. Mitigating climate change is a crucial component of the 2030 SDGs, categorized as 'Climate action'. Despite rapid economic growth, China still faces energy poverty in the household sector, with inadequate access to modern energy, especially in rural areas. Simultaneously, China has set ambitious goals for carbon emission peaking and neutrality. Examining the interplay between these global challenges enhances our understanding of potential policy tools that could address both issues simultaneously.

This study introduces a new energy poverty assessment system specifically designed for China, and examines the variations in the energy poverty index and residential carbon emissions across different policy scenarios. The primary objective is to offer scientific support to China in achieving its future objectives of alleviating energy poverty and reaching carbon peaking.

1.1 Basic Information about Energy Poverty

The term 'energy poverty' can be traced back to 'fuel poverty' in the UK (Bradshaw and Hutton 1983), which refers to 'the inability to afford adequate warmth at home'. Boardman (1991) defines people who need to spend 10% or more of their income on energy to maintain adequate indoor temperatures as 'fuel poverty'. Hills (2011) takes those who pay above-average fuel costs to maintain their basic needs and the residual income is below the official poverty line as fuel poverty. This is also called the 'Low-

income high-cost' (LIHC) standard. Both the 10% line and LIHC have been adopted by the UK government to define fuel poverty people (DECC 2013). The core of fuel poverty is the unaffordability of residential energy consumption. Then a significant body of research on energy poverty has emerged from the UK to worldwide in the 2000s, especially in developing areas. The core issue of energy poverty focuses on the inaccessibility of modern energy (such as electricity and natural gas) needed for basic energy services like cooking, lighting, and heating (IEA 2010a). According to the UN, about 1.2 billion people still lack access to electricity and nearly 40% of the people in the world lack access to clean cooking fuels (UNDP 2018).

Nowadays, the general concept of energy poverty could be divided into 'fuel poverty', which corresponds to the affordability of modern energy for the cost of heating, mainly in developed regions like the UK and Ireland (Healy & Clinch, 2002), and 'energy poverty', which is a broader concept, tends to recognize the availability and access of modern energy services for basic need, mainly in developing areas (Li et al., 2014; Bouzarovski & Petrova, 2015). Amidst political turmoil in the world today, there are emerging concerns regarding energy security, and rising energy prices are exacerbating the issue of energy poverty. At the same time, helping countries transition to a clean energy system while meeting growing energy demand is one of the biggest challenges of our time. Achieving a "Just Transition" for all to develop a low-carbon economy is a significant and urgent task. 'No poverty' and 'affordable and clean energy' have been listed as United Nations 2030 sustainable development goals (SDGs).

China's energy poverty has the features of both fuel poverty and energy poverty (Wang et al. 2015). In China, although the access to electricity has already attained 100% since 2013, the population with access to clean cooking is just 64% by 2019 (IEA et al. 2021), hence indicators for energy poverty measurement need to apply to China. Besides, given that China is experiencing socio-economic transformation as well as energy transition, policies like 'rural poverty alleviation', 'photovoltaic power development in rural areas', 'clean winter heating renovation' and 'biomass energy promotion' have

been implemented in recent years, which affect residential energy consumption level and structure, but how these policies will contribute to regional energy poverty situation have not been analyzed. Energy poverty alleviation is significant for achieving economic poverty alleviation and realizing energy transition and long-term social development goals in China.

1.2 Impact of Energy Poverty

As one of the manifestations of poverty, energy poverty impacts the health and quality of residents' lives, as well as social and economic progress and the establishment of a fair social system (Cabraal et al., 2005; Bouzarovski, 2018; Zhang et al., 2019).

1.2.1　Health

Energy poverty can have a profound impact on various aspects of health, including indoor air quality, access to basic health services, and overall quality of life. Studies have shown that households living in energy poverty are more likely to suffer from respiratory diseases, eye irritation, and skin irritation due to exposure to indoor air pollution caused by the use of traditional biomass fuels for cooking and heating (World Health Organization. Regional Office for Europe, 2007; González-Eguino, 2015; Thomson et al., 2017; Kahouli, 2020). Additionally, cold temperature rises the risk of human illness and mortality by placing thermal stress on the body and affecting the immune system and the blood and cardiovascular system (Healy 2003; Hood 2005). Numerous studies have examined the effect of energy poverty on families with children, revealing that parents in energy-poor households are at a higher risk of experiencing depression. Additionally, children in such families may encounter reduced calorie intake, poorer health, developmental setbacks, and a greater likelihood of being hospitalized (Lawlor and Wisser 2022). In addition to physical vulnerabilities, various studies have highlighted the educational and mental health challenges that families with children living in energy poverty may face. A study conducted by Mohan (2021) analyzed the impact of household energy poverty on the mental health of parents with

young children, and showed that households experiencing energy poverty have a greater likelihood of both maternal and paternal depression.

Moreover, the lack of access to modern energy services can result in increased poverty, decreased economic opportunities, and reduced quality of life, which can all contribute to poor health outcomes. Addressing energy poverty is essential for improving public health and reducing health inequities. In conclusion, the literature highlights the significant impact of energy poverty on health, emphasizing the importance of addressing this issue comprehensively and sustainably.

Besides, investigations on time series in Chinese urban areas have consistently revealed a significant correlation between temporary spikes in air pollution levels and elevated mortality rates, household air pollution from solid fuels was highest in middle and southwestern under-developed provinces (Yin et al. 2017) (Fig. 1). Studies analyzed the spatial distribution of PM2.5 concentration and premature mortality attributed to PM2.5 in cities at the prefectural level and above in China in 2016, results indicate that five diseases associated with PM2.5 exposure accounted for more than 1.5 million premature deaths in 2016 (Zheng et al. 2021). Studies also show that significant progress has been made in reducing pollution from ambient PM2.5 and household burning of solid fuels in recent years through extensive emission control measures, but PM2.5 concentrations in China continue to surpass the Air Quality Guideline set by the World Health Organization (WHO) for the entire population (Yin et al. 2020). Thus, energy poverty alleviation also plays a crucial role in reducing the risk of diseases or death rate related to PM2.5 exposure.

Death from Ambient PM pollution
2017 (thousand)

- 0.60 − 2.80
- 2.81 − 16.90
- 16.91 − 28.20
- 28.21 − 50.10
- 50.51 − 78.90

Death from household air pollution
from solid fuels 2017 (thousand)

- 0.30 − .1.80
- 1.81 − 5.30
- 5.31 − 9.30
- 9.31 − 15.80
- 15.81 − 27.90
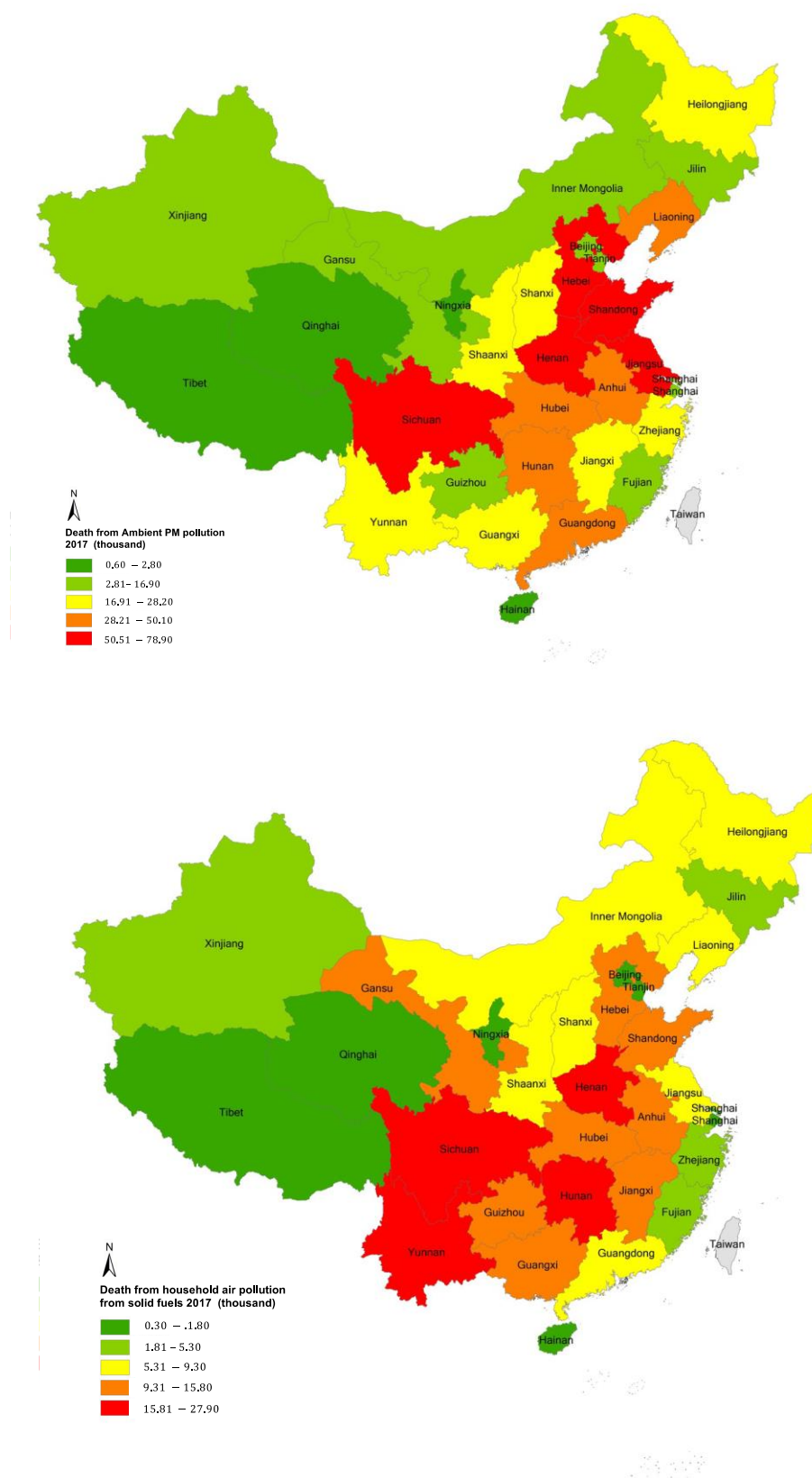
Fig. 1 Deaths attributable to ambient particulate matter pollution & household air pollution 2017[1]

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[1] Data source: Yin et al., 2017.

1.2.2 Economic Development

The study of Kraft & Kraft (1978) from the US shows a causal relationship between GNP to energy consumption, demonstrating a connection between development and energy use. Then the strong connection between energy consumption and economic development has since been verified by several studies (Acharya & Sadath, 2019; Bridge et al., 2016; Costantini & Monni, 2008; Doğanalp et al., 2021; Ghodsi & Huang, 2015; Martínez & Ebenhack, 2008). Energy poverty can limit the ability of individuals and communities to participate in the economy, which in turn contributes to poverty and socio-economic exclusion.

Energy is generally regarded as having two distinct uses: residential and productive (Cabraal et al. 2005). Residential uses of energy are expected to have a beneficial effect on the quality of life and enhance living standards. The productive use of energy, especially in rural areas, is expected to bring about higher rural productivity, increased economic growth, and a boost in household income and employment opportunities. Energy services not only affect farm income by improving efficiency and productivity by substituting animal and human labor with machines but also in other aspects such as time and resource savings, indirect benefits generated by lighting and communication, as well as many other positive impacts on non-agricultural business environments. In addition to increasing farm incomes, modern energy services have the potential to enhance the informal aspects of rural livelihoods by alleviating much of the daily drudgery experienced by impoverished rural communities. For instance, rural populations typically spend significant amounts of time each day gathering fuelwood, dung, and water. As biofuels are an inefficient source of energy (especially for cooking), they must be collected in large quantities. By providing rural communities with access to improved stoves and modern cooking fuels, this time could be redirected towards income-generating, educational, or other productive pursuits.

1.2.3 Social Welfare and Justice

Access to energy is a basic human need and a human right, and the absence of such access can have serious consequences for the health, education, and livelihoods of individuals and communities.

Energy poverty can exacerbate social and economic inequalities (Cabraal et al. 2005; Moniruzzaman and Day 2020). People living in poverty are more likely to suffer from energy poverty, as they often cannot afford the high costs of energy services. Compared with high-income groups, low-income groups spend more on living energy costs to meet household survival needs, and cannot easily escape from economic poverty, which could also limit opportunities for socio-economic mobility. This can lead to a vicious cycle of poverty, in which people are trapped in a state of deprivation and disempowerment and are unable to escape their circumstances. Access to modern energy is also related to education and gender equity. Children and women are often the primary collectors of biofuels in areas where modern energy is not readily available or affordable. Children and women are often the primary collectors of biofuels in areas where modern energy sources are not readily accessible or affordable. For children, the lack of electricity not only increases the threat to their safety but also limits the time and quality of their learning. To make matters worse, female children spend more time collecting traditional biomass energy sources and have lower levels of education. In addition, females are exposed to kitchen air for longer periods and are more vulnerable to health damage. The study illustrates that people living with chronic energy under services have more difficulty integrating and have lower educational completion. Advancements made towards achieving SDG 7 (affordable and clean energy) can be viewed as a strategy for accomplishing other SDGs and upholding the principle of "Leave no one behind".

1.3 Energy Poverty and Climate Change

Energy poverty and climate change are interconnected issues. On one hand, the use of

inefficient and polluting energy sources due to energy poverty would intensify climate change by adding to the overall greenhouse gas emissions. At the same time, energy consumption leads to greenhouse gas emissions. According to Chakravarty & Tavoni (2013), energy poverty alleviation will increase energy consumption, thus increasing carbon emissions. On the other hand, climate change has the potential to worsen energy poverty by disrupting energy systems and intensifying environmental and economic stresses. And the poor are always the most directly affected by climate change. The IPCC Fifth Assessment Report on Climate Change points out that climate change can hinder the process of poverty reduction in many countries, trigger new types of poverty, and lead poor people into a vicious cycle of disaster and poverty. Climate change and extreme weather events have caused serious damage to people's lives, property, livelihood patterns and infrastructure in China, and vulnerable areas and poor groups generally lack the capacity and resources to cope with climate risk shocks. Besides, energy poverty levels may increase as a result of strong climate change action (Ürge-Vorsatz and Tirado Herrero 2012).

Tackling both problems simultaneously can promote sustainable and fair energy solutions that benefit all. The synergies and tensions between energy poverty and carbon emissions exist in particular when considering energy consumption and efficiency. By promoting clean energy, energy efficiency and improved energy distribution, carbon emissions can be reduced and sustainable energy solutions can be provided to poor areas.

1.4 Research Objectives

Energy poverty, which refers to the lack of access to or affordability of modern energy, encompasses various interconnected dimensions such as poverty, energy, environment, and climate change. Its impact on sustainable development within human society cannot be underestimated. Concurrently, the current dependence on fossil fuels for energy consumption in human activities results in the release of greenhouse gases into

the atmosphere, thus significantly contributing to global climate change. An in-depth examination of the intricate relationship between these two global issues would enhance our understanding of the policy tools that could be effectively implemented to address both problems simultaneously.

Turning our attention to China, we find a complex landscape. On one hand, as the largest developing country, China has undergone remarkable economic growth. However, energy poverty persists within the household sector. On the other hand, China has also set ambitious targets for itself, aiming to reach carbon emissions peak by 2030 and achieve carbon neutrality by 2060. Considering that there is no consensus regarding the measurement of energy poverty, this study sets out to establish a new energy poverty assessment system specifically tailored to China. By doing so, it seeks to analyze the fluctuations in the energy poverty index (EPI) and residential carbon emissions over recent years. Furthermore, this research also involves the simulation of EPI and residential carbon emissions under various policy scenarios. The goal is to provide scientific support to aid China in achieving its future objectives of alleviating energy poverty and reaching carbon emissions peak.

Overall, this study aims to shed light on the intricate relationship between energy poverty and climate change, with a specific focus on the context of China. By developing an appropriate assessment system and analyzing the changes in energy poverty index and residential carbon emissions, it seeks to offer valuable insights and evidence-based recommendations that can inform effective policies for tackling energy poverty and achieving carbon neutrality in the country.

1.5 Framework

This research is organized as follows:
- Chapter 2 provides a comprehensive review of the concepts and measurements related to energy poverty, poverty and climate change, as well as the intersection

of energy poverty and climate change. It identifies the existing research gap in the field, highlighting the need for further investigation.

- Chapter 3 explains the selection of indicators, outlines the methodology and describes the data sources utilized. It also presents the data sources utilized for the study. Additionally, a new multidimensional measurement of energy poverty is proposed, along with the presentation of three different scenarios simulated in this research.

- Chapter 4 illustrates the results obtained from analyzing historical data and the three different scenarios. It offers a detailed analysis and discussion of the factors contributing to these outcomes, providing insights into the current status quo of energy poverty and carbon emissions.

- Chapter 5 further expands on the discussions by exploring other socioeconomic factors related to energy poverty and carbon emissions. It then draws conclusions based on the research findings, presents policy recommendations, and identifies the need for further study in this field.

Chapter 2. Literature Review

2.1 Conceptual Development of Energy Poverty

The concept of energy poverty was first brought up and developed in the UK. The initial concept is 'fuel poverty' by Bradshaw & Hutton (1983), which refers to the inability to purchase energy services. Boardman (1991) then defines households that cannot afford sufficient energy services as 'fuel poverty', people who need to spend 10% or more of their income on energy to maintain adequate indoor temperatures. Based on this, Reddy (2000) expanded the concept as the inability to independently obtain sufficient, affordable, anticipated, safe, and environmentally friendly energy services to support the regional economy and human development. Hills (2011) takes those who pay above-average fuel costs to maintain their basic needs and the residual income is below the official poverty line as fuel poverty. This is also called the 'Low-income High-cost' (LIHC) standard. The core issue of fuel poverty is the unaffordability of residential energy consumption and more commonly used for developed countries like the UK and Ireland.

Residential energy consumption in developed countries is dominated by modern clean energy. Energy poverty (or called fuel poverty) in those areas is mainly manifested in the high cost of living energy or the inability to pay enough heating costs to maintain indoor temperature. Taking Europe as an example, according to data from 2020, households in the EU relied on natural gas for 31.7% of their final energy consumption, while electricity accounted for 24.8%. The use of renewables and wastes made up 20.3% of the total energy consumption, while oil and petroleum products contributed 12.3%. In EU households, space heating accounts for about 62.8% of total energy consumption. According to the UK government (DESNZ 2023b), the proportion of fuel-poor households reached 22.1% in 2010, and it declined to 13.1% by 2021 (Fig. 2). Increased energy efficiency, higher incomes and lower energy prices improved the situation of fuel poverty household (BEIS 2022). In 2022, however, due to the impact of the post-

COVID and the energy crises caused by increased energy tax and unstable energy supplies, which have a negative impact on the resident's income and energy prices, there is a slight regression in fuel poverty levels.
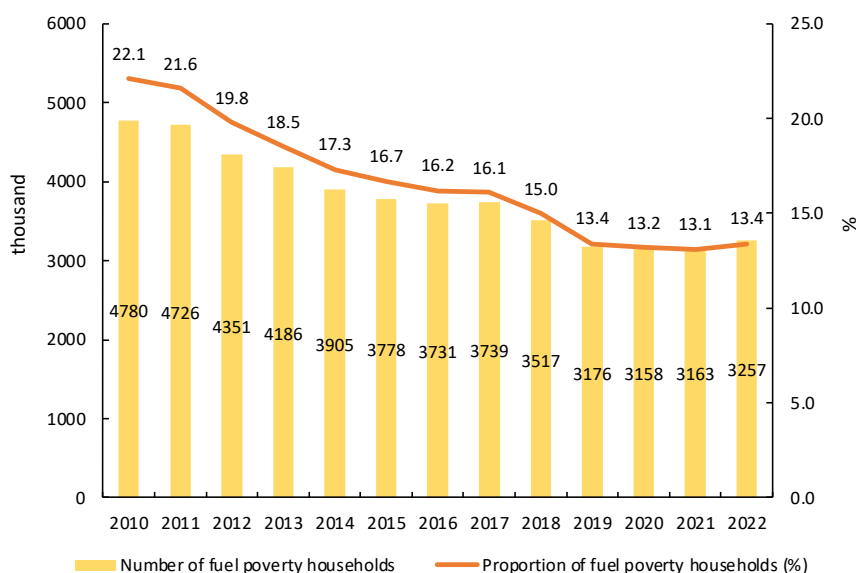
Fig. 2 Fuel poverty households in the UK (2010-2022)[2]

As studies began to shift worldwide in the 2000s, especially in developing countries, energy poverty focuses more on the inaccessibility of modern energy (such as electricity and natural gas) needed for basic energy services like cooking, lighting, and heating (IEA 2010a). Practical Action (2012) defined energy poverty as "the lack of adequate modern energy for basic needs of cooking, warmth and lighting, and essential energy services for schools, health centers, and income generation".

Energy poverty in developing countries is more manifested in the dependence on traditional biomass energy and the low level of electricity use. According to the UN, about 1.2 billion people still lack access to electricity and nearly 40 percent of the people in the world lack access to clean cooking fuels (UNDP 2018). By 2018, Latin America and the Caribbean as well as Eastern and South-Eastern Asia had made significant strides, achieving access rates of over 98% (Fig. 3). However, the remaining deficit in access to necessary resources is largely concentrated in sub-Saharan Africa,

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[2] Data source: https://www.gov.uk/government/statistics/fuel-poverty-trends-2023

impacting approximately 548 million individuals, which amounts to 53% of the population (UN-Statistics Division 2020).
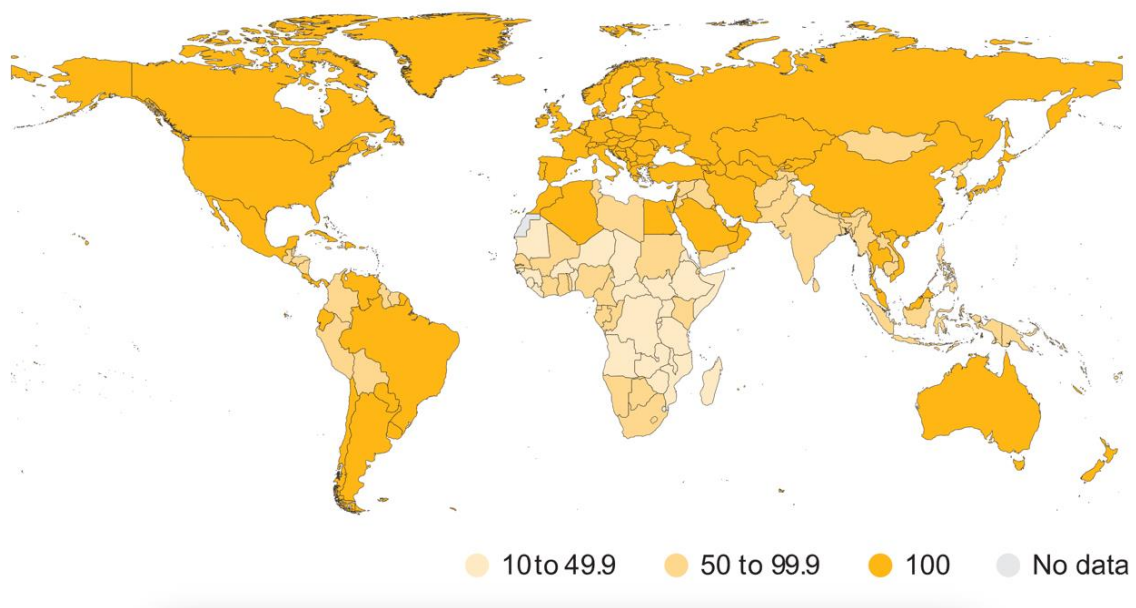
Fig. 3 Proportion (%) of the population with access to electricity (2018) [3]

The current widely accepted concept of energy poverty includes two types of definitions, fuel poverty and energy poverty, respectively with the core issues being the unaffordability of modern energy (mainly for the developed regions) and the inaccessibility of modern energy (mainly for the developing areas) (Li et al., 2014; Bouzarovski, 2018). Since the expression '*energy poverty*' is generally used worldwide, which includes both unavailability and unaffordability, this research uses 'energy poverty' as well.

2.2 Energy Poverty Measurement

There is no consensus on the measurement of energy poverty so far, scholars have proposed their own methods for different countries or regions. The main measurements of energy poverty could be generally systematized into single dimension and multidimensions.

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[3] Figure source: https://unstats.un.org/sdgs/report/2020/goal-07/

For one-dimensional approaches, the most common methods are from economic perspectives. Boardman (1991) brought up the '10% indicator', which means a family will be regarded as energy poverty if their energy expenditure is more than 10% of their household income. The low-income-high-cost (LIHC) indicator by Hills (2011) takes those who pay above-average fuel costs to maintain their basic needs and the residual income is below the official poverty line as energy poverty. The UK government has adopted both the '10% line' and LIHC as official standards. According to Foster et al. (2000), the average energy consumption of household that lives below the national minimum subsistence income is taken as the 'fuel poverty line'. In addition to the indicators mentioned above, there are also non-income-based indicators. Minimum-end use is also a one-dimensional approach but from energy consumption perspective, which refers to the household's minimum amount of energy needed to meet the basic requirement (Barnes et al., 2011).

For multidimensional approaches, scholars have made many related attempts. IEA developed the Energy Development Index to measure energy use in developing countries (IEA 2010b). Mirza & Szirmai (2010) developed a composite index by collecting data from a designed Energy Poverty Survey, including the frequency of energy collection or purchase, participation status of family members, time spent, distance, mode of transportation, etc., which evaluates the energy inconvenience for households and energy shortfall. Nussbaumer et al. (2012) constructed the Multidimensional Energy Poverty Index (MEPI), taking six indicators, namely cooking fuel type, indoor pollution, access to electricity, household appliances (fridge), education (radio or TV), and telecommunication. Practical Action (Organization) (2012) proposed the Total Energy Access Method that measured three aspects: the availability of electricity, household fuels and mechanical power. The UK government introduced a new indicator, the Low Income Low Energy Efficiency (LILEE), to measure fuel poverty from 2016. LILEE takes those households 'with a Fuel Poverty Energy Efficiency Rating (FPEER) of band D or below', meanwhile 'whose residual household income would be below the official poverty line if they were to spend their modeled

energy costs, as fuel poverty'. But the aforementioned studies consider only energy accessibility or only affordability. Some scholars develop different multi-indicator methods from the complex interaction of accessibility and affordability dimensions for various regions by taking different indicators, generally about households' access to electricity or other modern energy, energy supply and consumption level, energy price, financial situation, energy-consuming appliances use and ownership, etc. (Bekele, Negatu, and Eshete 2015; Bezerra et al. 2022; Bonatz et al. 2019; Gupta, Gupta, and Sarangi 2020; Khandker, Barnes, and Samad 2010; Khanna et al. 2019; Okushima 2017; Omar and Hasanujzaman 2021; Papada and Kaliampakos 2016; Ssennono et al. 2021; Wang et al. 2015; Ye and Koch 2023; Zhang et al. 2019) (Table. 1). Table. 2 lists the specific indicators that commonly used in previous studies.

Table. 1 Literature review of energy poverty measurements

Study & Region	Measurement	Indicators/Methodology
Boardman (1991); UK	10% indicator	Energy expenditure is more than 10% of the household income
Hills (2011); UK	Low-income-high-cost (LIHC)	Pay above-average fuel costs to maintain the basic needs and the residual income is below the official poverty line
DESNZ (2023a); UK	Low income low energy efficiency (LILEE)	Low energy efficiency (with a Fuel Poverty Energy Efficiency Rating of band D or below) and low income (residual household income would be below the official poverty line if they were to spend their modeled energy costs)
Foster et al. (2000); Latin America and the Caribbean	Fuel poverty	The average energy consumption of household that lives below the national monetary poverty line
Barnes et al. (2011); Bangladesh	Minimum-end use	The household minimum amount of energy needed to meet the basic requirement
Mirza & Szirmai (2010); Rural Pakistan	Energy Inconvenience Index	Energy deficiency indicator and energy inconvenience indicator, including frequency of energy collection or purchase, participation status of family members, time spent, distance, mode of transportation, etc.
Nussbaumer et al. (2012); Africa	Multidimensional Energy Poverty Index (MEPI)	Six equal-weighted energy accessibility indicators: cooking, lighting, household appliances, education, and communication
Practical Action (Organization), (2012); Kenya, Nepal and Peru	Total Energy Access Method	Energy availability indicators from three aspects: family fuels, access to electricity, and mechanical power

Bekele et al. (2015); Ethiopia	MEPI	Measuring incidence and intensity of energy poverty with five dimensions: cooking fuels, indoor air pollution and sources, electricity availability, possession of energy/electrical appliances, and use of these appliances.
Papada & Kaliampakos (2016); Greece	Integrated Assessment of Energy Poverty	Conducting a primary survey which records objective data on energy expenses and subjective perceptions about housing conditions.
Okushima (2017); Japan	Multidimensional Energy Poverty Index	A household is identified as energy poverty if only it failed meeting all three dimensions: cost of energy, income, and energy efficiency of housing.
Khanna et al. (2019); South and Southeast Asia	Weighted average of the four energy poverty indicators (WAEPI)	Four energy poverty indicators: access to electricity, availability to modern energy and technology, total energy supply, and total final energy consumption. By self-setting different weight scenarios.
Khandker et al. (2010); India	Energy Poverty Line	Taking three indicators' groups: household characteristics, village characteristics and village-level energy price. By a log-linear function and Tobit regression analysis.
Gupta et al. (2020); India	Household Energy Poverty Index (HEPI)	Taking 15 indicators grouped into five broad dimensions: possession of electrical appliances, monthly per capita expenditure, exposure to indoor pollution, use of clean fuels and accessibility and geographic conditions. By principal component analysis method.
Wang et al. (2015); China	Comprehensive Evaluation Index	Taking 23 indicators grouped into four categories: energy service availability, energy consumption cleanliness, energy management completeness, and energy affordability and efficiency. Weights for each indicator are reckoned by a data-driven approach.
Zhang et al. (2019); China	Multidimensional Index	Taking 'households using solid fuel for cooking' as accessibility and 'energy–income ratio' as affordability. Then combine affordability and accessibility with equal weight.
Bonatz et al., (2019); China, Germany	Energy Poverty Index	Taking ten indicators into six groups, including electricity, clean fuels, alternatives, energy price, income, and efficiency. The weights of each indicator are assigned by experts' consultant.
Ssennono et al., 2021; Uganda	Multidimensional Energy Poverty Index	Three dimensions: energy access, cooking solution, electricity service & appliance, 13 indicators in total. Equally weighted for each dimension (1/3) and then equally weighted for the indicators within each dimension. Weight accessibility and affordability equally (0.5 each) and assign weights for the binary indicators differently.

Omar & Hasanujzaman, 2021; Bangladesh	Multidimensional Energy Poverty Index	Similar with Nussbaumer et al., 2012. Cooking, lighting, household appliances ownership, and communication. Different weights are assigned based on importance.
Bezerra et al., 2022; Brazil	Multidimensional Energy Poverty Index	Three dimensions: physical access (cooking fuel, electricity); appliance ownership (space cooling, communication, food reservation), affordability (energy expenditure ratio). Each dimension is weighted equally, and the indicators are also equally weighted within each dimension.
Ye & Koch, 2023; South Africa	Multidimensional measure	Access: clean fuels for cooking, lighting, space heating and water heating; Affordability: the ratio of household required energy expenditure to total expenditure.

Table. 2 List of energy poverty measurement indicators from the literature review

Indicators	Description (Unit)
10%	Energy expenditure is more than 10% of the household income (%)
Low income high cost (LIHC)	Pay above-average fuel costs to maintain the basic needs and the residual income is below the official poverty line
Access to electricity	The ratio of population that has access to electricity (%)
Reliability of electricity supply	Annual power supply reliability (%)
Forest Area	Percentage of geographical area of a district under forests (%)
Energy inconvenience	Frequency of energy collection or purchase (frequency)
	Time spent (hours)
	Participation status of family members (including children) (Yes/No)
	Distance (km)
	Mode of transportation (type)
Home appliances	Ownership of refrigerator (count or Yes/No)
	Ownership of air conditioning (count or Yes/No)
	Ownership of TV or radio (count or Yes/No)
	Ownership of kitchen fans (count or Yes/No)
Cooking fuel type	Access to clean fuel for cooking (Yes/No)
Energy efficiency	Energy efficiency standards and labeling for household appliances and buildings (Yes/No)
Final energy consumption by energy carrier	Household electricity consumption (kWh)
	Household natural gas consumption (m^3)
Energy price	Electricity price ($/kWh)
	Gas price ($/$m^3$)
Income	Household disposable income
	Difference of the ratio between energy expenditure and income (%)
Air pollutants	Residential SO2 emissions
	Residential PM emissions

2.3 Energy Poverty Alleviation

2.3.1   Developed Countries

Energy efficiency, income and energy price are regarded as three main key drivers of energy poverty in developed countries (BEIS 2022; Lawlor and Wisser 2022). Therefore, the policies of developed countries to alleviate energy poverty mainly focus on the above three aspects.

The UK government has had a sustained focus on fuel poverty since 2001. As required under the Warm Homes and Energy Conservation Act 2000, the British government first published *The Fuel Poverty Strategy* from 2001 and then *The Annual Report on Fuel Poverty Statistics* since 2011. Tackling fuel poverty has been a major priority for the government and a subsidy mechanism has been established. For example, individuals who were born before 26th September 1956 may be eligible to receive a sum ranging from £250 to £600 to assist them in covering their heating expenses, which is called "Winter Fuel Payments".[4] There are also "Cold Weather Payments", which will be paid to those whose area's average temperature is recorded as or forecast to be at or below zero degrees Celsius for a continuous period of 7 days, and "Warm Home Discount", which is "a £150 discount on your bills if you get Pension Credit or live in a low-income household". The provision of energy bill support in 2022/23 is believed to have prevented an extra 350,000 households from experiencing fuel poverty in 2022 (BEIS 2022).

In Ireland, national-level strategies and policies have also been put forward, including "Warmer Homes: A Strategy for Affordable Energy in Ireland" in 2011, "Updated National Action Plan for Social Inclusion 2015-2017" and Strategy to Combat Energy Poverty in Ireland in 2016, and "National Energy and Climate Plan 2021-2030" in 2020. There are three broad approaches for tackling fuel poverty (Lawlor and Wisser 2022):

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[4] Source: https://www.gov.uk/winter-fuel-payment

first, improving energy efficiency, i.e., by providing State grants via the Sustainable Energy Authority of Ireland (SEAI) for retrofitting; second, income support, e.g., subsidizing energy bills, including the energy components of the Household Benefits Package; and consumer protection measure, including the development of codes of practice and the setting out of customer rights by the independent regulator.

For Germany, the government considers energy poverty as an element of a comprehensive collection of social policies aimed at addressing poverty more broadly. In addition, ensuring energy affordability is one of the three objectives of the German energy transition. The national government has implemented various policies, some of which are aimed directly at addressing energy poverty. Basic social support encompasses all household living expenses, including energy costs, that are necessary for subsistence. Furthermore, the government may offer loans to cover outstanding energy payments to avoid disconnection, and in certain cases, may assume long-standing debts arising from energy costs. Although financial aid is available for energy efficiency enhancements, it is generally not directed specifically toward households experiencing energy poverty. The proportion of individuals who were unable to maintain a sufficient level of warmth in their homes decreased from 5.9% in 2008 to 5.0% in 2010, before rising to 5.3% in 2013, and then has declined again to 2.7% in 2018 (EPOV 2021).

2.3.2   Developing Countries

Energy poverty in developing countries is more manifested in the dependence on traditional biomass energy and the low level of electricity use, therefore, the main means for developing countries to alleviate energy poverty is to strengthen the construction of national infrastructure energy facilities and guide residents to change their living energy.

Brazil pays attention to power infrastructure construction. In 2003, the Ministry of

Mines and Energy of Brazil launched the "Light for All" plan, which is expected to achieve the goal of universal access to electricity in Brazil in 2014, with a total investment of 12 billion US dollars. As of 2010, the project has provided basic electricity services to 14.5 million people, and by 2020 Brazil's access to electricity rate has reached 100%[5]. The Brazilian government has established a distributed renewable energy system including solar power generation systems and biogas power generation systems in the Amazon region where the population without electricity is concentrated. The "Light for All" program not only alleviates energy poverty but also provides residents with opportunities to increase their income. More than one-third of Brazilian households have increased their household income after obtaining electricity (IEA 2010b).

India provides lower electricity prices and modern fuel subsidies for the poor to guide the economically poor to shift their domestic energy use from traditional fuels to modern energy sources through a price subsidy mechanism. To ensure that the economically poor can afford basic electricity expenses, Himachal Pradesh has set the price of electricity at $0.04/unit, which is 57% of the average cost of electricity supply; low-income groups in Gujarat pay $0.03/unit, which is 12% lower than the average cost of electricity supply. The Indian government hopes to achieve energy poverty alleviation by investing in renewable energy technologies. Despite the Indian government's ongoing efforts to increase access to electricity in rural areas, the electrification rate in rural areas is still much lower than in urban areas. And due to environmental, infrastructure and financial constraints, conventional thermal power plants are unable to meet the growing demand. The Indian government is funding the solar industry in the form of subsidies for manufacturers and consumers, attracts investment in small-scale hydropower plants through low-interest loans and low taxes, and is also committed to promoting modern biomass energy, including biogas.

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[5] Data source: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=BR

South Africa is one of the regions with the best solar energy conditions in the world. The South African government adapts to local conditions, promotes solar energy utilization equipment, and advocates clean energy transformation. In 2009, the South African Ministry of Energy implemented a plan to install 1 million solar water heaters to alleviate regional energy poverty. In 2010, *Kuyasa* clean development mechanism project and *Zanemvula* solar energy water heater project were implemented in Cape Town and Port Elizabeth respectively. The implementation of the project has significantly reduced the consumption of traditional fuels, while providing employment opportunities and increasing residents' income (Wlokas 2011).

2.4 Poverty and Climate Change

Although combining poverty alleviation with climate change policy integration is not an immediately apparent area of focus since these two issues hold distinct positions on the agendas of local politics, poverty alleviation and carbon emission reduction are intricately linked. Actively implementing emission reductions to address climate issues would unavoidably curtail the development of the energy and related sectors, lead to industrial transformation in the long run, affect residents' employment and life, and increase uncertainty and unknown risks in the implementation of poverty alleviation projects in the short term (Alexander 2016; Jin et al. 2018; Madlener 2020; N. Zhang et al. 2017; Q. Zhang et al. 2017).

However, the introduction of the Green New Deal (GND), which was the first comprehensive plan to combine climate change mitigation and the elimination of economic inequality, makes it possible to address both issues simultaneously. The research of Galvin & Healy (2020) shows that the U.S. Green New Deal has a positive impact on both climate change mitigation and inequality reduction. A significant number of the technical advancements emerging from efforts to mitigate climate change would directly advantage individuals with low incomes, including 100% renewable electricity, improving the energy efficiency of buildings, reducing industrial pollution,

etc. Relative studies on GND have also been conducted in Canada, the UK, and other parts of the world including Europe and Asia (Brown et al. 2023; MacArthur et al. 2020; Smol 2023). The GND energy roadmaps by Jacobson et al. (2019) call for a 100% transition from conventional energy sources to wind-water-solar energy (WWS) by 2050 in 143 countries. The findings indicate that WWS requires less energy, incurs fewer costs, and generates more job opportunities.

Some scholars have done relevant research on China's poverty alleviation and carbon reduction. Jin et al. (2018) investigate relationships between carbon emissions, employment rate and poverty-alleviation index. The result shows that China's average carbon emission is significantly positively correlated with the poverty-alleviation index and employment rate. Study also has shown that China can cap carbon emissions at the 2015 level without hindering economic development by introducing a CO_2 tax, tax-funded rural poverty alleviation then could benefit boost domestic consumption (Glomsrød et al. 2016).

Furthermore, there is a unique poverty alleviation project in China, as one of ten government-led large-scale poverty alleviation programs, called photovoltaic poverty alleviation (PVPA). It refers to the construction of photovoltaic power plants in poor areas with implementation conditions, and the distribution of photovoltaic power generation revenue in the form of growing the collective economy of poor villages and subsidizing the personal income of poor households in the form of industrial poverty alleviation. Studies have shown that PVPA makes positive contributions to income increase, poverty reduction, as well as emission mitigation (Han et al. 2020; Li et al. 2018; Xu et al. 2022). It also alleviates energy poverty by improving energy service availability and household energy consumption structure and use behavior, diversifying job opportunities and increasing potential sources of income (Li et al. 2023; Zhao et al. 2023).

2.5 Energy Poverty and Climate Change

Energy poverty and climate change are interconnected issues. Tackling both problems simultaneously can promote sustainable and fair energy solutions that benefit all. The synergies and tensions between energy poverty and carbon emissions exist in particular when considering energy consumption and efficiency. In addition to the above literature related to the Green New Deal, there has been some research on the relationship between energy poverty and climate change directly, although it has been relatively limited. On one hand, energy consumption leads to greenhouse gas emissions. Chakravarty & Tavoni (2013) constructed a model to show that an encompassing energy poverty eradication policy to be met by 2030 would increase energy consumption by 7%, thus increasing additional carbon emission and increasing global temperature by up to 0.13°C. On the other hand, as nations endeavor to fulfill their nationally determined contributions (NDCs) and combat climate change, they are adopting increasingly ambitious measures. Nevertheless, these initiatives have sparked apprehensions about energy poverty and resulted in a global escalation of energy costs, partially attributable to stricter environmental regulations, and this situation has presented difficulties for individuals struggling with affordability (Belaid et al. 2023).

However, Boardman (2009) and Bouzarovski (2018) believed that, "in the long term, many of the aims of climate change and energy poverty policy are mutually reinforcing". International Energy Agency (2012) presents a renewable energy transformation policy scenario to achieve modern energy access globally, which would only increase global energy demand by 1% in 2030 and CO_2 emissions by 0.6%. Ürge-Vorsatz & Tirado Herrero (2012) validate the co-benefits of both in the buildings field, where deep energy efficiency shows the most significant synergy. Their research also shows that addressing energy poverty through only income is difficult because the additional income is not necessarily used for energy consumption, subsidized energy price is a temporary solution. Streimikiene et al. (2020) develop an indicators framework with 15 indicators to evaluate low carbon energy transition in two European countries,

Lithuania and Greece, and then use this framework to analyze how climate change mitigation policies in households affect energy poverty. According to the result, policies to promote renewables in households and renovation of residential buildings should be implicated. M. Pereira et al. (2019) investigate the impact of reliable and secure electricity access on rural communities in Brazil in the context of a shift towards modern energy. The results show that accessing modern energy sources, particularly electricity, is crucial in meeting the fundamental needs of the populace while concurrently diminishing the energy emissions intensity by incorporating more efficient energy resources and equipment. The long-term policies should highlight energy efficiency and the use of renewable energy in households (Chapman and Okushima 2019; Serrano-Medrano et al. 2018; Streimikiene et al. 2020). Climate change mitigation actions have potential co-impacts to other policy and development goals, e.g., the SDGs (Cohen et al. 2021), energy access, security and air pollution (van Vliet et al. 2012), social and economic policies (Galvin and Healy 2020; Watson et al. 2014).

There are also several studies about carbon emissions and energy poverty in China. Bonatz et al. (2019) compare the energy poverty and low carbon development of Germany and China. The result shows that China should prioritize the provision of high-quality energy carriers for cooking and heating, especially in rural areas. Expanding renewable energies, for example, small-scale photovoltaic, presents an opportunity to address not only carbon emissions but also energy poverty. Dong et al. (2021) examine whether a low-carbon energy transition can alleviate energy poverty by analyzing the influence of natural gas consumption (NGC) on energy poverty in China. The findings suggest that increased NGC can be an effective way to mitigate energy poverty in the country, with varying impacts across different regions. Zhao et al. (2021) assess energy poverty's effect on carbon emission in China by the SYS-GMM method. The result indicates that energy poverty may accelerate the increase of carbon emissions in China.

2.6 Research Gap and Originality

Energy poverty is a multifaceted issue that arises from several factors, such as limited access to clean and modern energy and the financial strain caused by low income and high energy expenses (Boardman 2009). Although a consensus on measuring energy poverty is yet to be established, the indicators presented in the table above can provide valuable reference points for most regions. However, it is essential to account for the distinct characteristics and circumstances of each region to develop an index system that is both effective and comprehensive. By tailoring the measurement approach to local contexts, a more accurate understanding of energy poverty can be achieved, facilitating targeted interventions and policy measures.

While single-dimensional approaches to measuring energy poverty are straightforward and require less data, they come with inherent limitations. For instance, the "10% indicator" can be excessively influenced by energy prices and may overlook income disparities (Romero, Linares, and López 2018). The Low-Income High-Costs (LIHC) indicator relies on defining specific thresholds, which can be challenging in practice. In the case of China, research conducted by Wang et al. (2015) revealed that the average household's energy expenditure accounted for only 3.3% of income in 2011, well below the "10% line" used in countries like the UK. Therefore, utilizing the "10% line" as a measure of energy poverty in China would be inappropriate. Furthermore, due to China's diverse climate and varying levels of development, there is no universal definition or standard for minimum energy usage or expenditure that can adequately address basic living needs. When employing multidimensional indicators, it becomes crucial to carefully tailor the selection of metrics to the specific context of different regions, taking into account factors such as economic development, climate conditions, living habits, and data availability.

In the case of China, energy poverty exhibits characteristics of both accessibility and affordability. While access to electricity reached 100% coverage in 2013, only 64% of

the population had access to clean cooking solutions by 2019 (IEA et al. 2021). Recognizing China's dedication to promoting cleaner and renewable energy sources while addressing poverty, recent policies have been introduced to foster the development of clean energy. These policies include the implementation of the clean winter heating renovation policy in northern regions, which involves transitioning from coal to gas or electricity for heating systems. Additionally, there are supportive policies in place for photovoltaics and biogas adoption in rural areas. Consequently, when evaluating energy poverty in China, it becomes crucial to incorporate indicators that accurately capture the impact of these policies.

Furthermore, there is a notable research gap in examining the synergies between energy poverty and climate change, with existing studies often treating these topics in isolation. Hence, this research endeavors to address this gap by focusing on how changes in energy structure can simultaneously affect energy poverty and residents' carbon emissions. By exploring these interconnections, it aims to cultivate a more comprehensive understanding of how alterations in energy systems can concurrently impact energy poverty and contribute to carbon emissions. This enhanced understanding will pave the way for the formulation of more effective strategies and policies that tackle both energy poverty and climate change.

2.7 Conclusion

This chapter provides a literature review of the development of the concept of energy poverty, measurement methods, and the relationship between climate change and poverty and energy poverty. Since firstly brought up as 'fuel poverty' in the UK, a significant body of research on energy poverty has emerged from the UK to worldwide. As one of the manifestations of poverty, energy poverty impacts the health and quality of residents' lives, as well as social and economic progress and the establishment of a fair social system. Nowadays, the general concept of energy poverty could be divided into 'fuel poverty', which mainly corresponds to the affordability of clean and modern

energy in developed regions like the UK and Ireland, and 'energy poverty', which tends to recognize the availability of modern energy services in developing areas. Although energy poverty has obtained wide focus in recent years, there is no consensus on the measurement of energy poverty. In addition to the household income and energy expenditure perspective, scholars also develop different multi-indicator methods from the complex interaction of accessibility and affordability dimensions for various regions by taking different indicators. Climate change mitigation actions have potential co-impacts to other policy and development goals, e.g., the SDGs, energy access, security and air pollution, social and economic policies, and also poverty and energy poverty alleviation. On one hand, implementing emission reductions to address climate issues would curtail the development of the energy and related sectors, lead to industrial transformation in the long run, affect residents' employment and life, and increase uncertainty and unknown risks in the implementation of poverty alleviation projects in the short term. On the other hand, it is possible to address both issues simultaneously.

Given the absence of a widely accepted measurement framework for energy poverty, this research aims to develop a novel energy poverty assessment system specifically tailored to China's context. Furthermore, there is a relative lack of research on the synergies between energy poverty and climate change, with existing studies often treating these subjects independently. Therefore, this research places significant emphasis on investigating how changes in energy structure concurrently impact energy poverty and residents' carbon emissions. By exploring these synergistic dynamics, a more comprehensive understanding of the intricate relationship between energy poverty and climate change can be achieved, enabling the formulation of more effective strategies and policies.

Chapter 3. Methodology and Data

3.1 Indicators Identification and Selection

Corresponding to the basic concept of energy poverty, this research developed new energy poverty measuring index (Table. 3) with three main categories, energy service availability, energy consumption and generation cleanliness, and household energy affordability and efficiency. Considering the availability of data and the actual situation in China, the selection of indicators is as follows:

(1) Energy service availability

Energy service can help reduce poverty (Cecelski, 2000), this research uses 4 indicators to reflect the adequacy of energy service access by assessing residential sector energy consumption and supply capacity. Access to electricity is a widely used indicator in many previous studies, but since it already attained 100% in China in 2013 and the reliability of power supply has already been greater than 99.8% (Yuan, Pu, and Liu 2021), the indicators of access to electricity and power supply reliability are not suitable for China. Since the Chinese government has been promoting the use of natural gas in recent years, we use natural gas consumption and coverage rate to capture modern energy access and supply. Besides, because of the great difference in temperature and climate between the south and the north, we processed the heating consumption data by dividing the number of days with an average daily temperature less than 16 degrees to attenuate the effect of climate.

(2) Energy consumption and generation cleanliness

8 indicators were chosen to reflect the environmental friendliness of residential energy consumption and power generation in terms of green and modernized energy consumption structure. Share of modern fuels in total residential sector energy use shows the level of access to clean cooking facilities, which was used by IEA (2010) for the Energy Development Index, and the use of modern cooking fuel always serves as

an indicator in many studies too (Jayasinghe, Selvanathan, and Selvanathan 2021; Khandker et al. 2010). This study uses the similar indicator 'ratio of non-solid commercial fuel' to show residential clean energy structure, and 'ratio of the rural household taking straw as main cooking fuel in poor area' to reflect the cooking fuel use in rural areas. Renewable power generation especially micro-generation technologies will affect energy poverty level (Streimikiene et al. 2021), so the renewable power generation ratio was selected as an indicator in this research. Clean heating is an important part of the energy transition, and has a significant impact on rural lifestyle and energy poverty level (Zhang et al. 2021), therefore this paper newly added 'clean heating renovation' as an indicator to reflect the new energy transition policy of China. Air pollutants from residential source can reflect household energy structure and also related to health issues to some degree (Cabraal et al. 2005), and energy poverty has serious health concerns related to household air pollutions. So, we use the data of three main air pollutants from residential source and the number of kitchen hood (this is listed as household appliances below).

(3) Household energy affordability

7 indicators were selected for assessing the affordability of domestic energy, and security of energy consumption. The number of electric household appliances is highly related to the degree of electrification, the awareness of electricity utilization and families economic situation (Hölzer&Huba, 2007; Pereira et al., 2011), and has been widely used in many previous studies (Pereira et al., 2011; Pachauri & Spreng, 2004). According to the UK official report, energy efficiency, income and energy price are the three main key drivers of energy poverty (BEIS 2022). Households bear the cost burden of high energy prices in two distinct ways. Firstly, direct increases in fuel prices result in higher household bills for fuel-related activities such as heating, cooling and cooking. Secondly, energy and fossil fuel inputs required for producing goods and services for household consumption lead to higher prices of such items, ultimately impacting household expenditure (Guan et al. 2023). Education has a mitigating effect on energy poverty by the greater potential for increased energy conservation awareness and

income (Apergis, Polemis, and Soursou 2022). The higher the income, the lower the level of energy poverty.

According to the data from China Statistical Yearbook of House Survey and China Family Panel Studies, the national average households' energy expenditure accounted for only 3.2% of income for urban household and 4.19% for rural household in 2014, far less than the 10% line of UK and other developed regions like Japan. This is not because China has a lower level of energy poverty than the UK, but because the two are at different stages of development and have different household income levels and consumption habits. As for the CPI of residence water, electricity & fuels, because energy prices are currently under government control and subsidies, they are relatively stable. However, considering the future market-oriented reforms and factors such as peak and valley tariffs, it will still have an impact on consumer behavior. This research had also considered the subsidies as indicators. For the PV installation, however, the central government will no longer subsidize newly registered centralized photovoltaic power plants, industrial and commercial distributed photovoltaic projects, and newly approved onshore wind power projects, and implement grid parity from 2021. Only PV policy support items for rural poor households before 2020 can be queried. As for the subsidies for clean heating renovation projects in winter, there are differences among local governments from city to city, and the subsidies are gradually being reduced or cancelled. Therefore, due to data availability, these two subsidies were not selected as indicators eventually.

Table. 3 Categories and indicators for China's energy poverty evaluation

Tier 1 indicator	Tier 2 Indicator	Tier 3 Indicator	Unit	References
Energy Service Availability	Residential energy consumption and supply	Per capita electricity consumption	kWh per capita	(Barnes et al. 2011; Foster et al. 2000; IEA 2010a; Pachauri and Spreng 2004; Wang et al. 2015)
		Per capita natural gas consumption	m^3 per capita	
		Residential central heating area	m^2 per household	
		Gas coverage rate	%	

Energy consumption and generation cleanliness	Residential Energy structure	Clean commercial fuel ratio	%	(IEA 2010a; Jayasinghe et al. 2021; Khandker et al. 2010; Wang et al. 2015)
		Ratio of households taking straw as main cooking fuel in poor area	%	
		Clean winter heating renovation ratio	%	- (New)
	Energy generation structure	Biogas production in rural area	m^3 per household	(Cabraal et al. 2005)
		Non-thermal power ratio	%	(Streimikiene et al. 2020)
	Air pollutants from residential energy consumption	Household SO2 emissions	kg per capita	(Cabraal et al. 2005; Nussbaumer et al. 2012; Wang et al. 2015)
		Household PM emissions	kg per capita	
		Household NOx emissions	kg per capita	
Residential energy affordability	Energy-consuming appliances	Kitchen hood (exhaust fan)	count/hundred household	(Bekele et al. 2015; Gupta et al. 2020; Nussbaumer et al. 2012; Pachauri and Spreng 2004; Pereira et al. 2011)
		Water heater	count/hundred household	
		Refrigerator	count/hundred household	
		Air conditioner	count/hundred household	
	Residential energy affordability	Consumer price index for bills (water, electricity & fuel)	-	(Boardman 1991; Chapman and Okushima 2019)
		Educational Attainment	%	(Apergis et al. 2022)
		Disposable income	RMB per capita	(Boardman 1991; Chapman and Okushima 2019)

3.2 Methodology

3.2.1   Entropy Weighting Method

Several approaches are commonly employed for constructing measurement indices. Expert opinion involves consulting experts in the field to identify and select relevant indicators for index construction. Questionnaires can be distributed to gather opinions and suggestions from relevant stakeholders, enabling the analysis and integration of the collected data into the evaluation system. Alternatively, a weighted composite index approach can be utilized, which involves constructing a weighted average of individual indicators using predetermined weights that reflect their relative importance. In line with the selected indicators' characteristics, this research will employ a weighted composite index methodology for measurement.

For the weight assignment of indicators methods, equal weighting, expert consultant, self-setting weighting or Analytic Hierarchy Process (AHP) are relatively less objective. As an objective weighting method, Principal component analysis (PCA) helps to reduce the dimensionality of the data by identifying the most important components or factors that explain the majority of the variability in the data. However, it can result in some loss of information, and it is also sensitive to outliers in the data, which can have a significant impact on the results. The interpretation of PCA can be challenging at times, as the identified components or factors may lack a clear and straightforward interpretation. There is another objective weighting method, the entropy weighting method, which is also adaptive and comprehensive. By determining index weights through the entropy method, the problem of randomness and speculation that may exist in the subjective assignment method is overcome, and the problem of information overlap among multiple indicator variables can be effectively solved. This research will use the entropy weighting method for the energy poverty measurement.

In information theory, "entropy" measures the disorder level in a system. In the data

matrix $X = \{x_{ij}\}_{n \times m}$, which is composed of n evaluation schemes and m evaluation indicators, the greater the dispersion of data, the minor the information entropy, the more information provided, the greater the influence of the indicator on the comprehensive evaluation, and the greater the weight should be, and vice versa (Zou et al. 2006; Gray, 2011). The entropy method is widely used in comprehensive evaluation, for example, power quality (Ouyang et al. 2013), water quality (Sahoo et al. 2017), global clean energy development index (He, Jiao, and Yang 2018), investment risk assessment of coal-fired power plants (Yuan et al. 2019) and energy sustainability (Hou et al. 2021). The main steps of this method are as follows.

1) Normalization. Since the dimensions and properties of the 19 indicators are different, this research uses the min-max method to process the data to dimensionless measurements:

$$x'_{ij} = \frac{x_{ij} - \min x_j}{\max x_j - \min x_j} \quad \text{if indicators are positive relative} \tag{1}$$

$$x'_{ij} = \frac{\max x_j - x_{ij}}{\max x_j - \min x_j} \quad \text{if indicators are negative relative} \tag{2}$$

(i: evaluation province, i=1, 2…n; j: evaluation indicator, j=1, 2…n)

2) Calculate the proportion of the jth indicator of the ith province:

$$y_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{n} x'_{ij}} \tag{3}$$

3) Calculate the entropy value of the jth indicator:

$$e_j = -K \sum_{i=1}^{n} y_{ij} ln y_{ij}, \text{ where } K = \frac{1}{lnn} > 0 \tag{4}$$

4) Calculate the coefficient of variation of the jth indicator d_j :

$$d_j = 1 - e_j \tag{5}$$

5) Calculate the weight of the jth indicator:

$$w_j = \frac{d_j}{\sum_j d_j} \tag{6}$$

6) According to the above formulae, the energy poverty index is calculated as follows:

$$\text{Energy Poverty Index} = \sum_j y_{ij} w_j \tag{7}$$

3.2.2 Carbon Emission Accounts

Energy consumption is considered to be the main contributor to carbon emissions (IPCC 2019). Since the 1990s, some developed countries have seen residential energy consumption surpass industrial sectors, leading researchers to acknowledge the carbon emissions resulting from residential energy consumption (Druckman and Jackson 2009; Weber and Perrels 2000; Zhu, Peng, and Wu 2012). The emission factor method is a commonly used method to calculate carbon emissions (as equation 8). The China Emission Accounts and Datasets (CEADs) has conducted provincial residential carbon emissions accounts based on residential energy consumption (Shan et al. 2016), but only direct emissions from fossil fuel were calculated; this study also includes emissions from residential heat and electricity consumption. As for the emission factors (EF), both the IPCC and NDRC provide default EF for the primary fossil fuels (Eggleston et al., 2006; NDRC, 2011). The EFs recommended by the IPCC and NDRC, however, are higher than the actual emission factors based on the measurements of 602 coal samples taken from the top 100 coal-mining regions in China (Liu et al. 2015; Shan et al. 2018). Thus, this study adopts the updated EFs (Table. 4).

$$Emissions = \sum AD_i \times EF_i \qquad (8)$$

$$Emissions_i = AD_i \times NCV_i \times CC_i \times O_i \qquad (9)$$

Where AD_i represents the fossil fuel consumption by the corresponding fossil fuel types i.

<div align="center">Table. 4 Emission factors by fuel types</div>

Fuel Type	EF
Raw Coal	1.83
Cleaned Coal	2.31
Other Washed Coal	1.33
Briquettes	1.6
Coke	2.96
Coke Oven Gas	11.67
Other Gas	6.02
Other Coking Products	2.59
Crude Oil	3.1
Gasoline	2.99

Kerosene	3.1
Diesel Oil	3.12
Fuel Oil	3.26
LPG	3.15
Refinery Gas	3.38
Other Petroleum Products	3.12
Natural Gas	2.16

Emissions from household heat and electricity consumption are also calculated by different emission factors. There are six regional girds of China in total (northern, northeastern, eastern, central, northwestern, and southern), covering different provinces (Fig. 4). The baseline emission factors for each regional grid differ due to data on electricity generation, fuel consumption for electricity generation, and the low heating value of the fuel used for electricity generation (Table. 5). Thus, the carbon emissions of different provinces are calculated with regional power grid EFs.

Table. 5 Regional power grid emission factors

Power Grid EF	2014	2015	2016	2017	2018	2019	2020
North	0.9288	0.9007	0.8627	0.8405	0.8268	0.8269	0.8203
Northeast	0.9845	0.9547	0.9483	0.9139	0.8852	0.8719	0.8624
East	0.7787	0.7570	0.743	0.7265	0.6911	0.6908	0.6826
Central	0.8477	0.8011	0.7689	0.7539	0.7242	0.7154	0.7103
Northwest	0.8312	0.7883	0.7579	0.7674	0.7707	0.7793	0.7628
Southern	0.7979	0.7631	0.7275	0.6894	0.6561	0.6565	0.6482

Fig. 4 Coverage of regional power grid of China

3.3 Data

3.3.1 Historical Data

Referring to previous studies and China's features and based on their relevance and quantifiability, 19 indicators were selected to construct China's energy poverty index system (Table. 3). Data of 30 provinces (or municipalities) of China from 2014-2020 are analyzed for this research. According to the description of the statistical yearbook, from 2013 onwards, the survey sample has been completely renewed and differs from previous years in terms of the overall population and selection methods of urban and rural residents, with a wider survey scope, and the statistical methods for urban and rural residents' disposable income, household consumption expenditure and other data have also changed. In addition, the electricity access rate in China has reached 100%

since 2013. For the above reasons, this study chose 2014 as the initial year rather than an earlier year. All seven years of data are obtained or calculated from Statistical Yearbooks by each province, China Energy Statistical Yearbook, China Rural Statistical Yearbook, China Yearbook of Household Survey, China Statistical Yearbook of Environment, China Meteorological Data Service Center, China Family Panel Studies, Poverty Monitoring Report of Rural China, and National Energy Administration Report (Table. 6).

Table. 6 Data source of all indicators

Tier 3 Indicator	Unit	Original Data Source
Per capita electricity consumption	kWh per capita	China Energy Statistical Yearbook;
Per capita natural gas consumption	m^3 per capita	Provincial Statistical Yearbook
Residential central heating area	m^2 per household	China Yearbook of Household Survey
Gas coverage rate	%	China Yearbook of Household Survey; China Rural Statistical Yearbook
Clean commercial fuel ratio	%	China Energy Statistical Yearbook
Ratio of households taking straw as main cooking fuel in poor area	%	Poverty Monitoring Report of Rural China
Clean winter heating renovation ratio	%	Ministry of Ecology and Environment and local department Report
Biogas production in rural area	m^3 per household	China Rural Statistical Yearbook
Non-thermal power ratio	%	China Energy Statistical Yearbook
Household SO2 emissions	kg per capita	China Statistical Yearbook of Environment
Household PM emissions	kg per capita	
Household NOx emissions	kg per capita	
Kitchen hood (exhaust fan)	count/hundred household	Provincial Statistical Yearbook China Rural Statistical Yearbook
Water heater	count/hundred household	
Refrigerator	count/hundred	

	household	
Air conditioner	count/hundred household	
Consumer price index for bills (water, electricity & fuel)	-	China Statistical Yearbook; Provincial Statistical Yearbook
Educational Attainment	%	
Disposable income	RMB per capita	

3.3.2 Defining Scenarios

We employ scenario analysis as a framework to ensure the coherent integration of diverse energy-related issues and to explore policies that facilitate a transition towards a sustainable development-oriented energy system. By leveraging the latest data and development trends, this research presents three distinct scenarios spanning the period of 2021-2035. These scenarios primarily differ in terms of energy consumption structure and factors directly linked to energy, such as the number of household appliances. Conversely, variables less directly associated with energy, including population, disposable income, and educational attainment, maintain consistent trends across all three scenarios. The starting year for these scenarios is 2021, selected as the most recent year with comprehensive historical energy data available for all provinces during the time of this research.

3.3.2.1 Business as Usual (BAU)

The Business as Usual (BAU) scenario serves to demonstrate the expected outcome based on the continuation of the current trajectory. It captures the effects of government policies and measures that were enacted or adopted by 2020, without considering any potential or likely future policy actions. Essentially, the BAU scenario represents a continuation of historical data and trends. It establishes a baseline that showcases the projected trends in energy poverty levels and household carbon emissions if there are no changes to the underlying energy demand and supply patterns.

In the BAU scenario, it is assumed that there will be a continued decline in household coal consumption, accompanied by a gradual increase in the share of modern energy consumption. These assumptions are adjusted slightly based on historical trends and the energy outlook of different provinces. Notably, key regions such as Beijing-Tianjin-Hebei, the Yangtze River Delta, and the Fen-Wei Plain will experience more pronounced changes in their energy consumption structure compared to non-key areas. This is due to stricter regulations on fossil energy consumption implemented in targeted air pollution prevention and control plans. Additionally, urban areas face more stringent requirements compared to rural areas, resulting in a more rapid transformation of their energy structure. These settings and dynamics are also applicable to the other two scenarios outlined below.

Table. 7 BAU scenario Assumption

	Item	Coal Products	Gasoline	Diesel	LPG	Natural Gas	Heat	Electricity
Urban	Key area	-20%	+5%	-5%	+1%	+8%	+2%	+8%
	Non-Key area	-10%	+2%	-2%	+2%	+5%	+2%	+5%
Rural	Key area	-10%	+2%	-5%	+2%	+5%	+1%	+3%
	Non-Key areas	-5%	+2%	-2%	+2%	+3%	+1%	+2%

3.3.2.2 Carbon emission reduction (CER)

Carbon emission reduction (CER) strategies concentrate on promoting behavior change and reducing home energy demand and consumption. These strategies aim to achieve a significant reduction in carbon emissions by adopting measures that result in a more

sustainable energy landscape. In the context of the CER scenario, several key assumptions are made to facilitate the reduction of carbon emissions.

Firstly, the CER scenario anticipates a sharper decline in coal consumption compared to the Business as Usual (BAU) scenario. Coal, being a high-carbon energy source, contributes significantly to carbon emissions. By reducing coal consumption, the CER scenario aims to mitigate the carbon footprint associated with energy generation. Furthermore, the CER scenario projects a more moderate increase in the consumption of natural gas, heat, and electricity compared to the BAU scenario. This implies that efforts are made to promote energy-efficient appliances, implement energy-saving measures, and encourage the use of cleaner energy sources. By reducing the reliance on fossil fuels and encouraging the adoption of cleaner alternatives, the CER scenario strives to minimize carbon emissions arising from home energy consumption. Behavior change plays a crucial role in the CER scenario. It encompasses encouraging individuals to adopt energy-saving habits, using energy-efficient appliances, and embracing renewable energy technologies. By focusing on behavior change and implementing measures to curb home energy demand and consumption, the CER scenario presents a pathway to achieve substantial carbon emission reductions.

Table. 8 CER scenario Assumption

	Item	Coal Products	Gasoline	Diesel	LPG	Natural Gas	Heat	Electricity
Urban	Key area	-40%	+3%	-8%	-1%	+5%	+1%	+5%
	Non-Key area	-20%	+1%	-5%	-1%	+3%	+1%	+3%
Rural	Key area	-20%	+1%	-8%	+1%	+3%	+0.8%	+1%
	Non-Key areas	-10%	-2%	-5%	+1%	+2%	+0.8%	+1%

3.3.2.3 Renewable Energy (REN)

The Renewable Energy (REN) scenario distinguishes itself from traditional approaches that primarily rely on projecting past trends and adjusting them based on known policy actions. Instead, the REN scenario intentionally selects a viable energy pathway that prioritizes the utilization of renewable energy sources and emphasizes energy efficiency. This strategic decision acknowledges the crucial role that renewable energy plays in addressing climate change and enhancing energy supply security. Extensive research has consistently demonstrated the substantial impact of renewable energy adoption and technological advancements in mitigating energy poverty (Lee et al., 2022; Rahman et al., 2021). By incorporating renewable energy solutions, the REN scenario offers a promising avenue for simultaneously tackling energy poverty and advancing sustainable development goals.

In the REN scenario, there is a deliberate emphasis on reducing reliance on coal, a slight decrease of LPG and fostering a rapid increase in the consumption of natural gas, heat, and electricity. This shift reflects a concerted effort to transition from high-carbon to low-carbon energy sources, aiming to reduce carbon emissions and mitigate environmental impacts. Additionally, the REN scenario incorporates improvements in emission factors for heat and electricity. Specifically, the emission factor for heat, which measures the amount of emissions produced per unit of heat generated, decreases significantly when natural gas is utilized instead of coal. For example, the emission factor drops from 0.11 when coal is used for heat generation to 0.062 when natural gas is employed. Furthermore, the REN scenario assumes a consistent decline in the grid emission factor, which refers to the amount of emissions produced per unit of electricity generated. It is projected to decrease by 0.5% annually. This reduction signifies an ongoing commitment to enhancing the environmental performance of the electricity generation sector. By continuously reducing the grid emission factor, the REN scenario contributes to the overall decrease in carbon emissions associated with electricity consumption.

The intersection between energy poverty measurement and residential carbon emission lies in 'energy'. Among all energy poverty measurement indicators, household electricity and natural gas consumption, and clean commercial fuel ratio vary directly with the energy consumption. Others will remain the same for the BAU scenario and CER scenario, and for the REN scenario, the growth rate will be higher than the historical trend, at the same time, there are slight adjustments according to different provinces.

By consciously selecting a feasible energy path that prioritizes renewable energy and energy efficiency, the REN scenario exemplifies a proactive and sustainable approach to energy planning. Through a combination of measures, including a shift away from coal, increased utilization of cleaner energy sources, and improvements in emission factors, the REN scenario strives to reduce carbon emissions while ensuring a reliable and secure energy supply. Ultimately, this scenario aligns with global efforts to combat climate change, promote sustainable development, and foster a transition towards a more environmentally friendly energy landscape.

Table. 9 REN scenario Assumption

	Item	Coal Products	Gasoline	Diesel	LPG	Natural Gas	Heat	Electricity
Urban	Key area	-50%	+3%	-8%	-2%	+8%	+2%	+10%
	Non-Key area	-30%	+1%	-5%	-2%	+5%	+2%	+8%
Rural	Key area	-30%	+1%	-8%	+2%	+5%	+1%	+5%
	Non-Key areas	-20%	+1%	-5%	+2%	+2%	+1%	+3%

In recent years, China has taken strides in accelerating the transformation of its energy structure and enhancing energy services through a series of government documents

issued at both the central and local levels. These policy measures aim to increase the proportion of renewable energy in power generation, achieved through the installation of additional PV and wind power equipment. Additionally, China is actively developing biomass energy based on local conditions and promoting domestic waste power generation in urban areas. Efforts are also being made to expand the coverage of natural gas pipelines, particularly in rural areas, with a focus on extending pipelines to villages and households. These policies lay a solid foundation for the realization of the REN scenarios, creating ample potential for their successful implementation.

Table. 10 A description of the assessed national documents and primary goals[6]

Related Official Document	Primary Goal
China Energy Outlook 2030 (2016.03)	By 2030, the installed capacity of photovoltaic and wind power will be increased by another 200GW respectively, and the scale of renewable energy power generation will continue to expand.
Opinions on accelerating the use of natural gas (2017.06)	By 2030, increase the proportion of natural gas in primary energy consumption to about 15%.
China Renewable Energy Outlook 2018 (2018.10)	China's total fossil energy consumption will steadily decline before 2035; The new PV installed capacity is about 80-160 GW/year, and the new wind power installed capacity is about 70-140 GW/year. By 2050, wind energy and solar energy will become the main force of China's energy system.
The 14th Five-year Plan (2021.03)	Establish numbers of clean energy bases with complementary versatility and increase the proportion of non-fossil energy in total energy consumption to about 20%. Annual per capita domestic electricity consumption reached about 1,000 kWh, and the coverage of natural gas pipeline network was further expanded.
China Nationally Determined Contributions (NDCs) (2020.12)	By 2030, the total installed capacity of wind and solar power will reach more than 1.2 billion kW. By 2030, China's carbon intensity will drop by more than 65% compared to 2005, non-fossil energy will account

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[6] Documents and plans promulgated at the provincial level are not listed here, but some were used as references when making minor adjustments for different provinces.

	for about 25% of primary energy consumption, and forest storage will increase by 6 billion m³ compared with 2005.
Notice on development and construction of wind power and photovoltaic power generation in 2021 (2021.05)	In 2021, the proportion of wind power and photovoltaic power generation in the total electricity consumption of the whole society will reach about 11%, and the follow-up will increase year by year to ensure that the proportion of non-fossil energy consumption in primary energy consumption will reach about 20% in 2025. The budget for national financial subsidy for household photovoltaic power generation project in 2021 is RMB500 million.
The 14ᵗʰ Five-year Renewable Energy Development Plan (2022.06)	In 2025, renewable power generation will reach about 3.3 trillion kilowatt hours; the scale of non-electricity utilization such as biomass heating, biomass fuel and solar thermal utilization will reach more than 60 million tons of standard coal.

Chapter 4. Results and Discussions

4.1 Energy Poverty Index (2014-2020)

Calculated according to the above steps, we could get China's multidimensional energy poverty index from 2014-2020 (Table. 11). A lower score indicates the energy poverty situation is better, while a higher index means relatively less energy secured.

Table. 11 China comprehensive energy poverty index (2014-2020)

Provinces	2014	2015	2016	2017	2018	2019	2020
Anhui	0.4067	0.3851	0.3440	0.3237	0.2601	0.2410	0.1997
Beijing	0.2252	0.2442	0.2076	0.1876	0.1606	0.1561	0.1503
Chongqing	0.3866	0.3717	0.3238	0.3123	0.2646	0.2518	0.2181
Fujian	0.2476	0.2366	0.2198	0.2126	0.2089	0.1954	0.1946
Gansu	0.6257	0.5806	0.4826	0.4381	0.3909	0.3446	0.2894
Guangdong	0.2892	0.2604	0.2476	0.2349	0.2164	0.1962	0.1851
Guangxi	0.4539	0.4093	0.3494	0.3165	0.2723	0.2172	0.1667
Guizhou	0.6562	0.5984	0.4568	0.4073	0.3606	0.3031	0.2617
Hainan	0.4303	0.3875	0.3573	0.3302	0.2860	0.2359	0.2039
Hebei	0.4246	0.4343	0.3352	0.3208	0.2964	0.2606	0.2277
Heilongjiang	0.6085	0.6096	0.5646	0.5417	0.4691	0.4405	0.3792
Henan	0.4807	0.4545	0.3671	0.3371	0.2855	0.2597	0.2238
Hubei	0.4342	0.4122	0.3859	0.3663	0.2956	0.2650	0.2135
Hunan	0.4423	0.4053	0.4116	0.3968	0.3585	0.3200	0.2311
Inner Mongolia	0.5962	0.5867	0.4674	0.4548	0.4068	0.3727	0.3753
Jiangsu	0.2131	0.1918	0.1799	0.1733	0.1642	0.1563	0.1549
Jiangxi	0.4066	0.3807	0.3584	0.3341	0.3006	0.2677	0.2177
Jilin	0.4889	0.4897	0.4638	0.4302	0.3779	0.3693	0.2685
Liaoning	0.3580	0.3561	0.2872	0.2729	0.2598	0.2453	0.2782
Ningxia	0.4981	0.5323	0.3195	0.3028	0.2602	0.2271	0.2368
Qinghai	0.6542	0.6265	0.4151	0.3659	0.3030	0.2725	0.2681
Shaanxi	0.5389	0.5193	0.4226	0.4019	0.3575	0.3273	0.2675
Shandong	0.2888	0.2831	0.2328	0.2125	0.1860	0.1793	0.1822
Shanghai	0.2585	0.2496	0.2091	0.2019	0.1913	0.1848	0.1799
Shanxi	0.5651	0.5734	0.3987	0.3837	0.3348	0.2970	0.2678
Sichuan	0.4310	0.4023	0.3611	0.3404	0.3054	0.2781	0.2084
Tianjin	0.2203	0.2197	0.2063	0.1897	0.1732	0.1654	0.1502
Xinjiang	0.5964	0.5733	0.4510	0.4140	0.3587	0.3006	0.2420
Yunnan	0.5619	0.5288	0.4924	0.4651	0.4182	0.3727	0.3098
Zhejiang	0.2279	0.2079	0.1925	0.1864	0.1713	0.1612	0.1619

4.1.1   Comprehensive energy poverty variations

The national composite Energy Poverty Index (EPI) demonstrates an overall declining trend from 2014 to 2020, indicating an improvement in the energy poverty level in China over time (Fig. 5). Analyzing the three categories of energy poverty indices, all exhibit downward trends, reflecting progress across the nation. Notably, the household energy affordability and efficiency index exhibits the most significant decrease, implying substantial advancements in energy affordability and the utilization of energy-efficient appliances. The energy service availability index is relatively higher while the energy consumption and generation cleanliness index is lower, indicating that the household consumption and supply of modern energy increased but are still rather insufficient, and the energy consumption and generation structures have become cleaner.
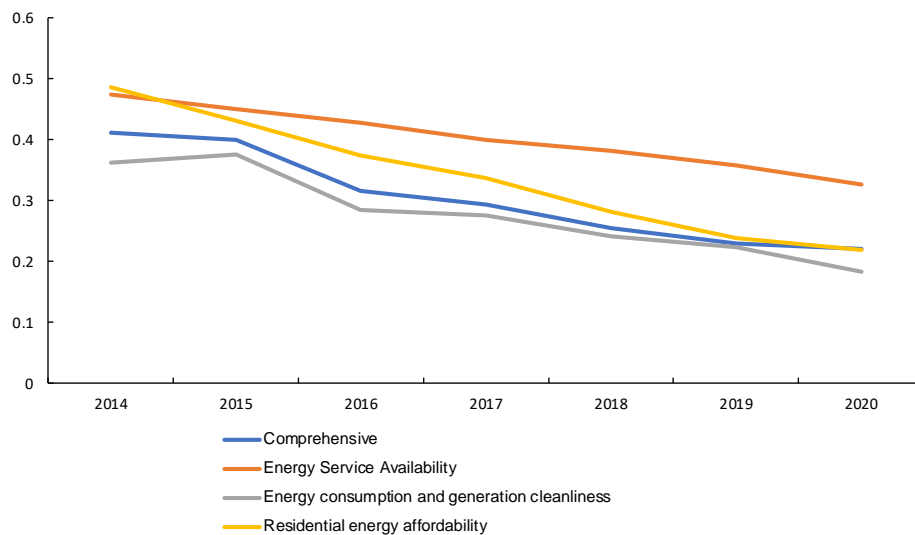
Fig. 5 China's Energy Poverty Composite Index (2014-2020)

The improvement in affordability is closely linked to the rapid economic progress of China in recent years, alongside the implementation of poverty alleviation policies. These policies encompass a range of initiatives, including the construction of roads and railroads, expanding access to electricity and the Internet, promoting tele-education and telemedicine, facilitating e-commerce for agricultural product sales, and establishing rural public service positions to enhance employment opportunities. As a result, the national average poverty incidence in rural areas has significantly declined from 7.63% in 2014 to 0.48% in 2020. Furthermore, the proportion of national average energy

expenditure relative to disposable income has also decreased from 3.18% to 2.47% for urban households and from 4.19% to 3.71% for rural households. The rise in income levels has enabled residents to afford more energy-consuming products, leading to increased energy consumption levels as well as the modernization and efficiency of energy consumption.

The acceleration of urbanization and the development of rural infrastructure, coupled with initiatives like the "West-to-East Gas Transmission" and "West-to-East Electricity Transmission", have contributed to the improved ability to provide modern energy services. Over the past years, both urban and rural areas have witnessed an enhancement in the national average gas coverage rates, as well as an increase in residential electricity consumption (Fig. 6). However, it is important to note that the utilization of modern energy remains insufficient, particularly in rural regions. The gas coverage rate in rural areas, on average, is still relatively low, with less than 50% of households having access to gas. In impoverished areas, approximately 25% of rural residents continue to rely on straw as their primary cooking fuel. Even in areas with gas coverage, residents may be hesitant to increase their consumption due to elevated fuel costs (Z. Wang et al., 2019).
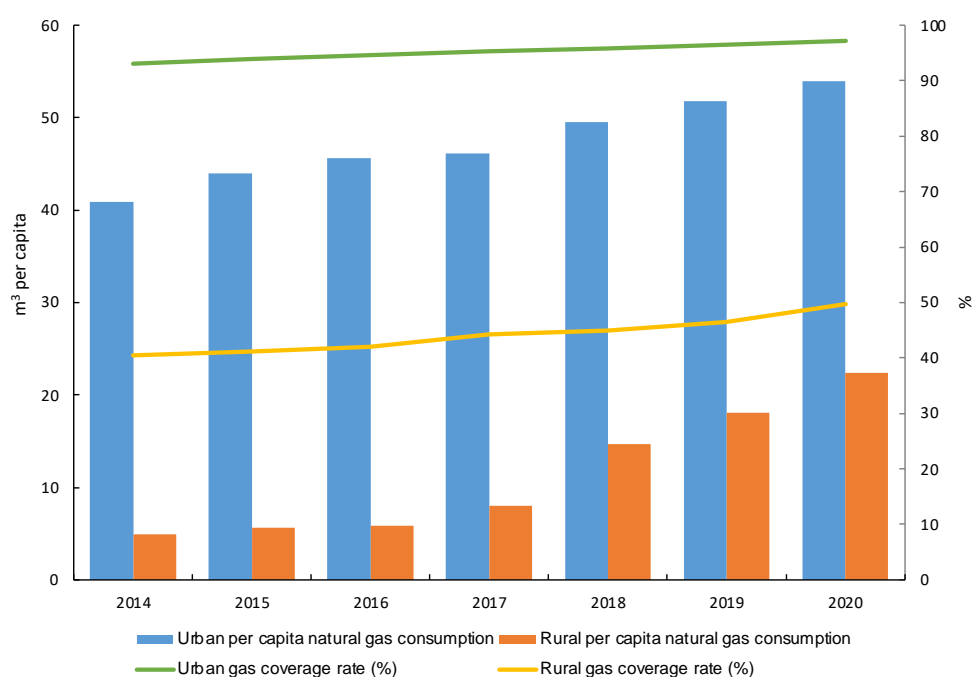
Fig. 6 Residential natural gas consumption and coverage rate (2014-2020)

With government support for renewable energy development, China has witnessed a gradual increase in the proportion of non-thermal power generation and a rise in the consumption of non-solid commercial fuels in recent years (Fig. 7). This shift reflects the country's commitment to transitioning towards cleaner and more sustainable energy sources. However, it is important to note that the rapid growth of renewable energy generation has also posed challenges related to integration. In 2016, the ratio of curtailed electricity to wind power and PV generation reached 17.2% and 10.3% respectively; in some areas, the curtailment rates even exceeded 40% (IEA 2018). In 2017, the National Development and Reform Commission and the National Energy Administration of China issued the *Measures for resolving curtailment of hydro, wind and PV power generation*, proposing more than twenty measures, including renewable energy power quota system, promoting the involvement of renewable energy power in market-based transactions, and improving the level of power transmission and cross-regional dispatch. For instance, "West-to-East Electricity Transmission" also promotes the curtailment of hydro, wind and PV power generation, reducing coal consumption in the eastern area. The cumulative West-to-East power supply of Yunnan Province exceeds 750 billion kWh during the 13th Five-Year Plan period, helping to reduce the consumption of standard coal in the eastern coastal region by about 200 million tons and reducing carbon dioxide emissions by about 500 million tons (Pu 2021), which effectively promotes the consumption of clean power in Yunnan Province, also contributes to the economic development of the eastern region and national pollution prevention. In 2019, the national average curtailment rate of wind power was reduced to 4%, and 2% of PVs, and the utilization rate of hydropower reached 96% (National Energy Administration 2020).
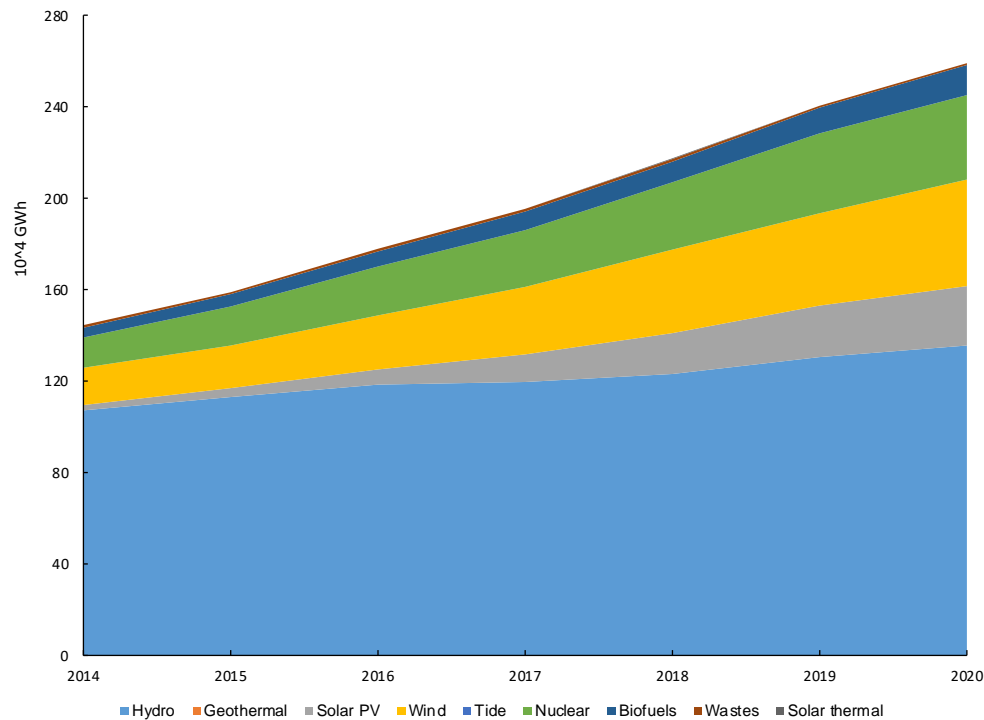
Fig. 7 Electricity generation from renewable sources (2014-2020)[7]

Besides, the State Council issued *the Air Pollution Prevention and Control Action Plan* in 2013, with 2017 as the target year, it proposed ten articles, including 35 comprehensive management measures for the control of air pollutants across China, and put forward clear targets for the reduction of PM10 and PM2.5 for cities nationwide and key areas (Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta). From 2005 to 2017, the percentage of Chinese households relying on solid fuels for cooking has declined significantly, dropping from 61% to 32%. This reduction can be largely attributed to the government's vigorous initiatives aimed at curbing the use of coal for household heating and cooking. Specifically, the prohibition of coal usage for these purposes in regions surrounding Beijing and other critical areas, coupled with the promotion of clean energy alternatives like natural gas, has facilitated the transition away from solid fuels throughout the country. SO_2, NOx and Particulate Matter emissions from the residential source have declined significantly since 2014 (Fig. 8). Studies show that for ambient PM pollution, the age-standardized death rate fell between 1990 and 2017, with the greatest reductions seen for household air pollution

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[7] Data source: https://www.iea.org/countries/china

from solid fuels, more pronounced decreases were seen from 2013 to 2017 (Yin et al. 2020) (Fig. 9).
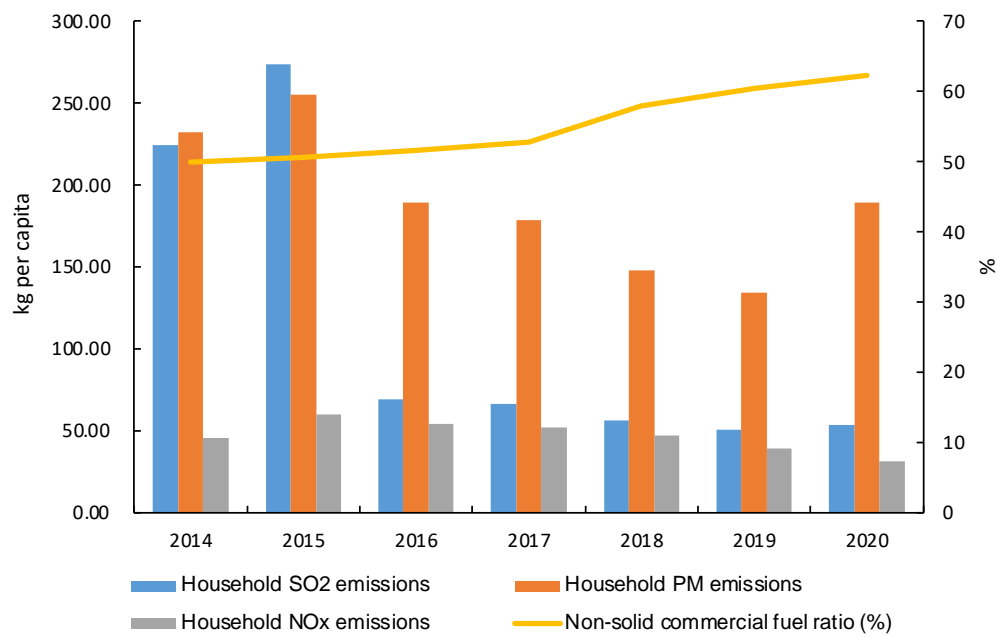

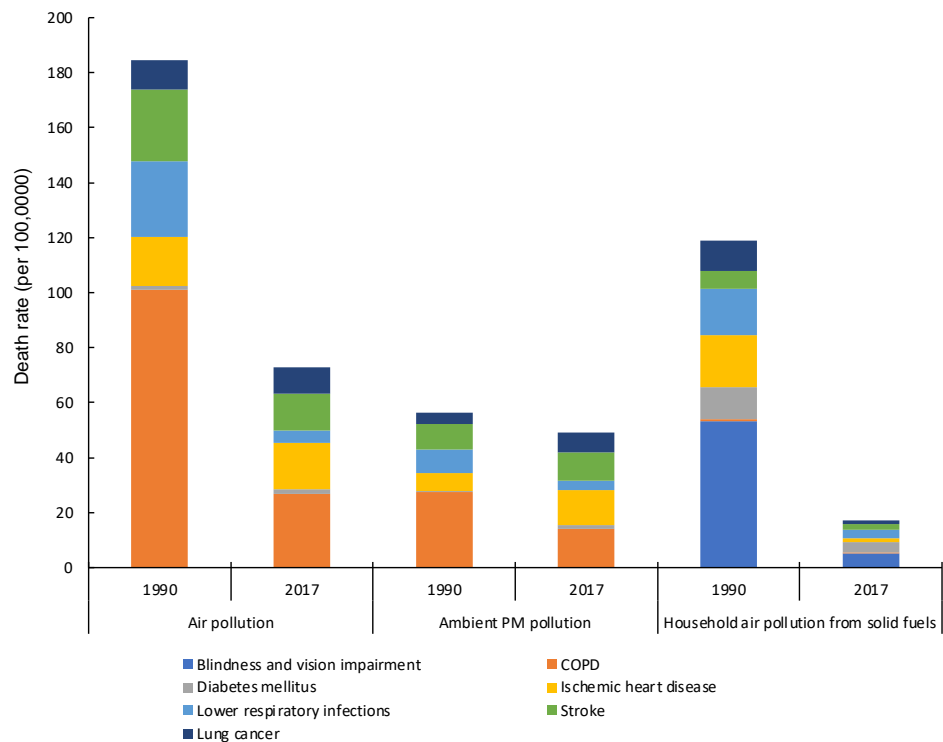Fig. 8 Household air pollutants emissions & non-solid fuel consumption rate

Fig. 9 Age-standardized death rate attributable to air pollution of China (1990 & 2017)[8]

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[8] Data source: Yin et al. 2020

4.1.2   Urban and rural energy poverty level

This study also evaluates the indices for urban and rural areas of China (Fig. 10), it shows that the energy poverty level has been improved in both urban and rural areas during the past few years. In addition to the increase in disposable income brought about by economic development, poverty alleviation policies have also played a role, especially in rural areas. For example, PV projects for poverty alleviation have been carried out in some rural areas, which can produce stable incomes for the poor and benefit local economic development (Y. Li et al., 2018). Small-scale solar facilities are installed on farmers' rooftops or in the courtyards, with the property rights and incomes belonging to the households; larger photovoltaic power plants are installed on land owned by village collectives or on unused hillsides, with revenues being distributed to poor households.

However, rural areas are still less energy secure compared with urban areas. There are substantial differences between urban and rural regions of many provinces, and the rural energy poverty index also varies widely across regions (Fig. 11). Despite the rising trend of urban and rural per capita disposable income as well as the access to modern energy, gaps between the disposable income levels of urban and rural residents are huge, and the consumption of modern energy of rural residents is still less than that of urban residents (Fig. 12). This also reveals a high correlation between social-economic status and energy security.
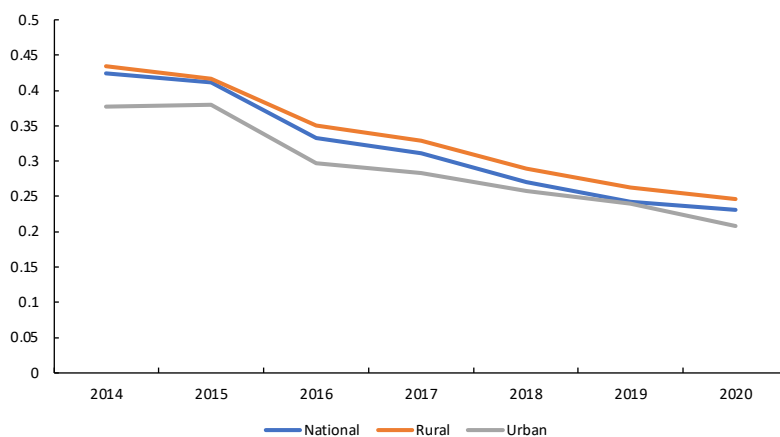

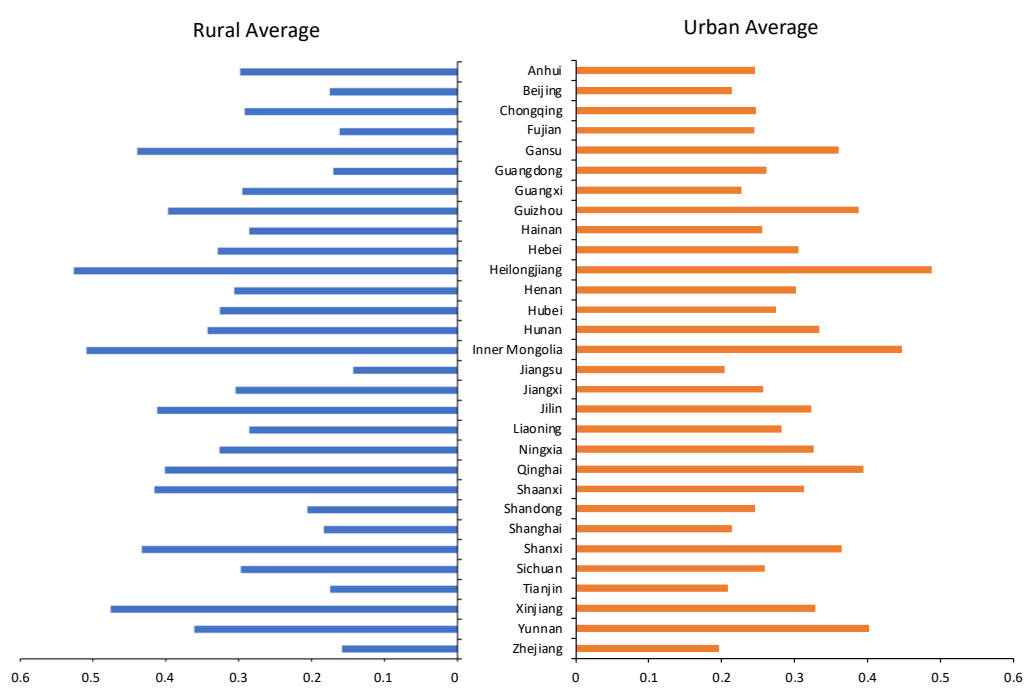Fig. 10 Urban and Rural Average energy poverty Index (2014-2020)

Fig. 11 Average energy poverty index across urban and rural areas in China
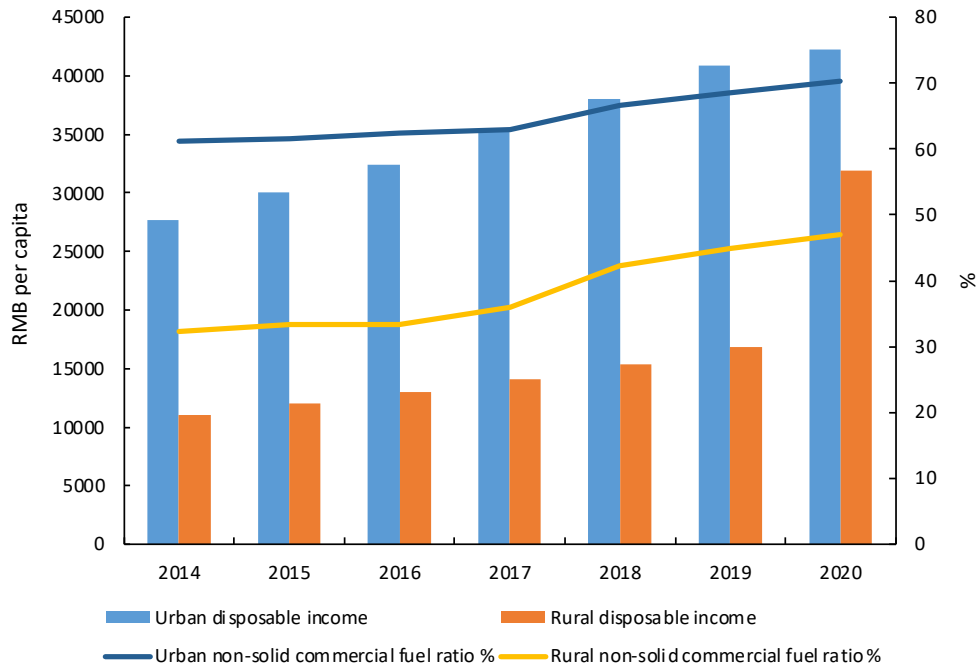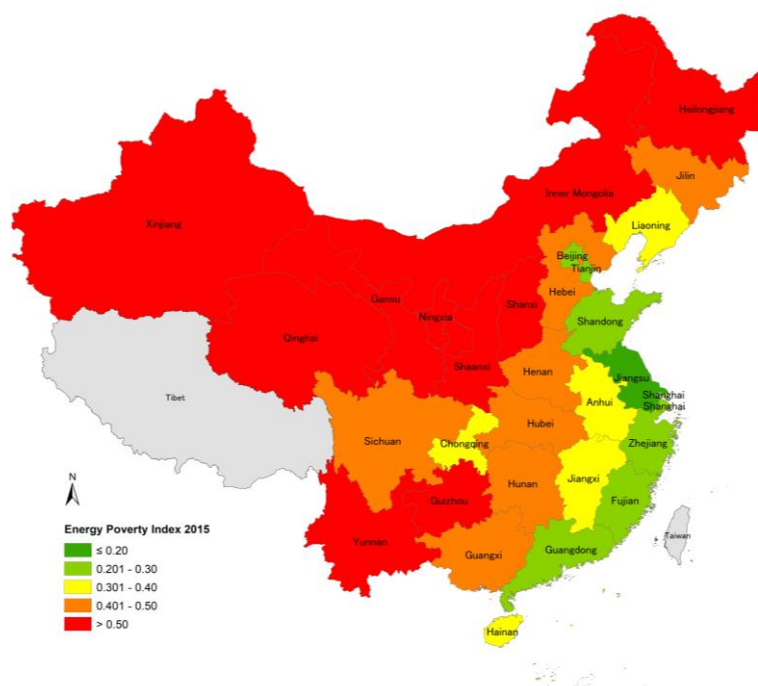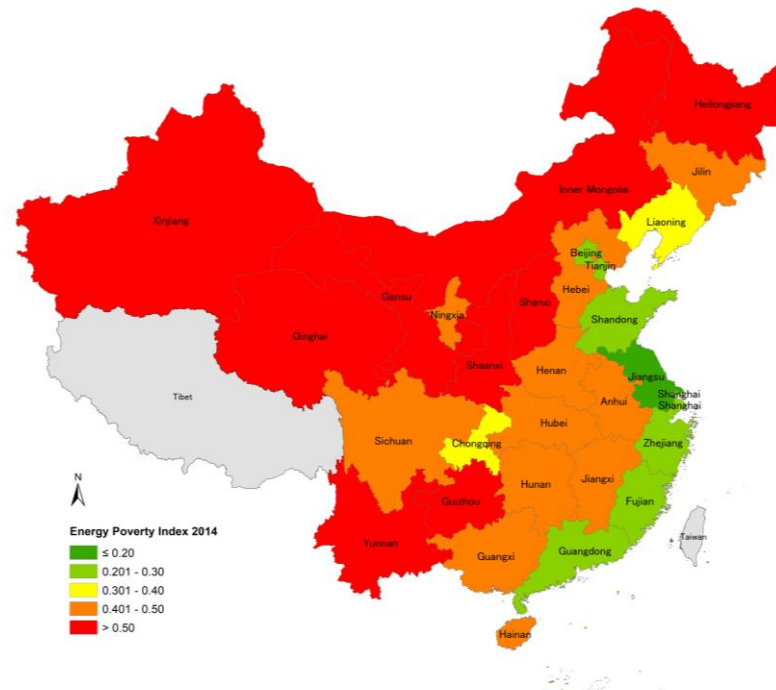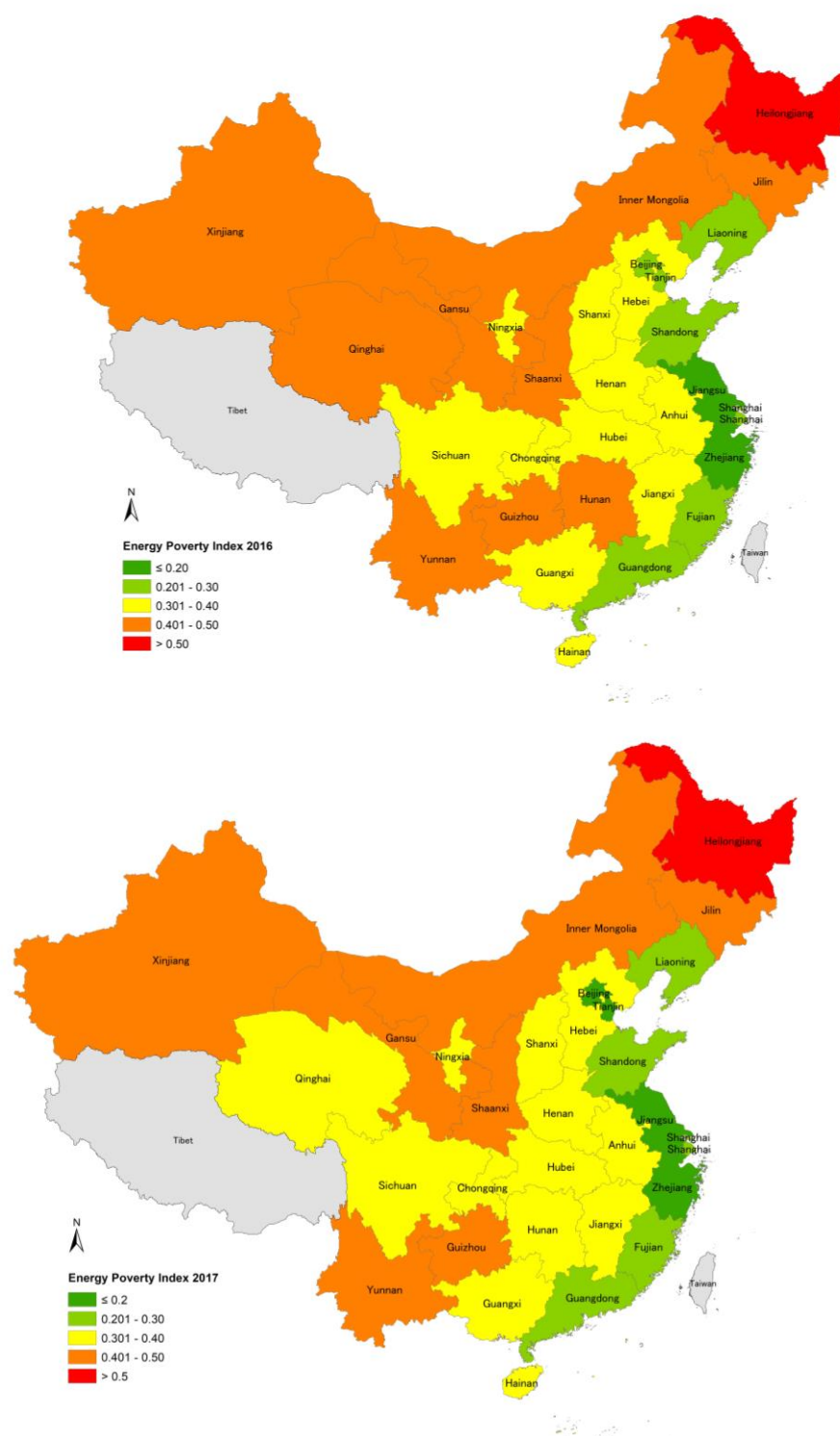

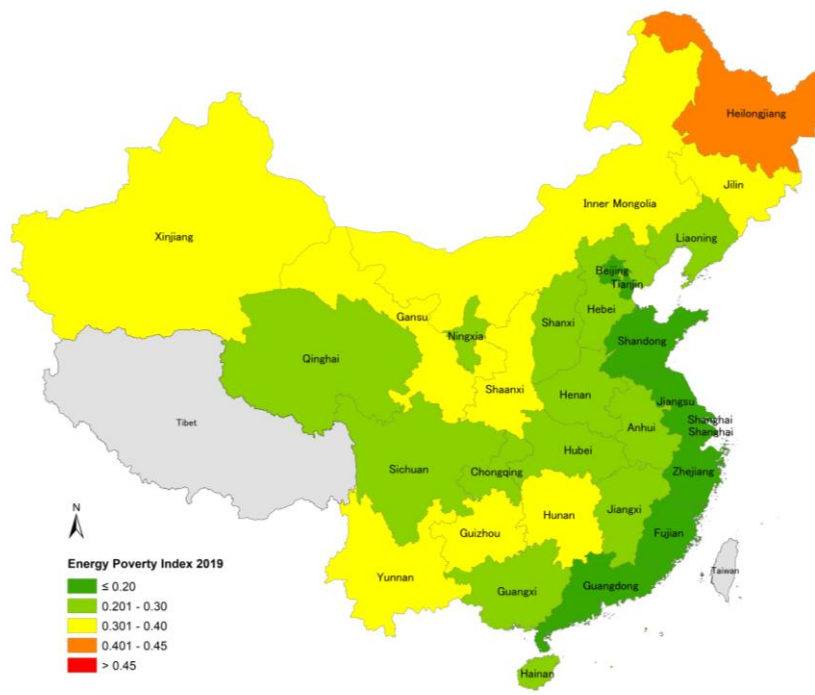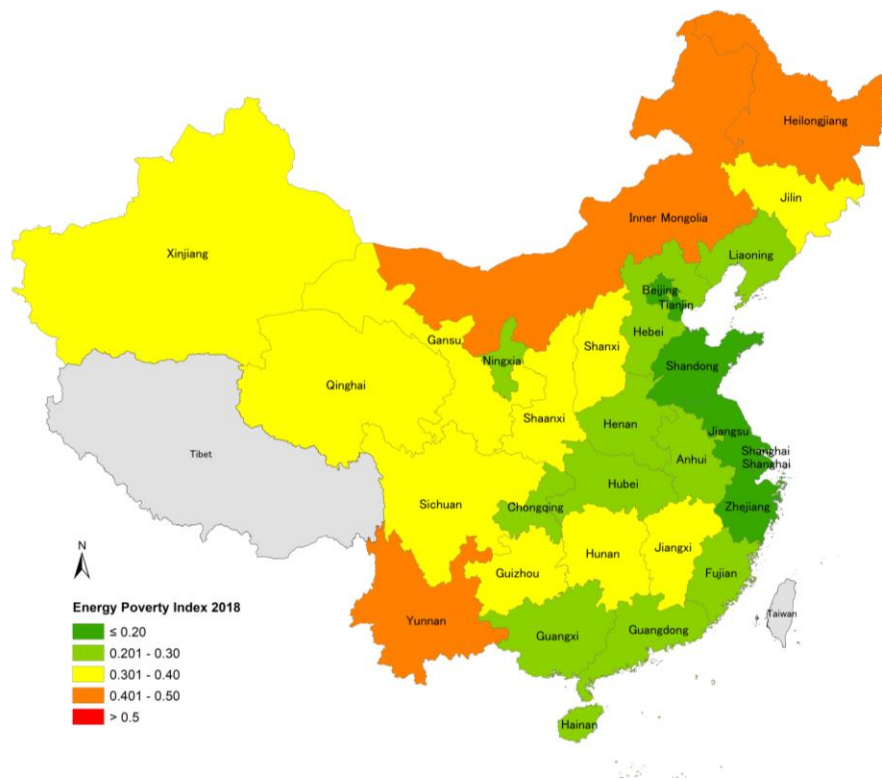Fig. 12 Urban and rural economic situation and modern fuels' access and consumption

4.1.3 Energy poverty variations by provinces

This study analyzed the spatial distribution of energy poverty in China (Fig. 13). Generally, the northern area shows obviously higher energy poverty index than the southern area of China; western regions are more energy-deprived compared with

eastern regions, especially northeast areas (Heilongjiang and Jilin), Inner Mongolia, northwest areas (Xinjiang and Shaanxi), and southwest provinces (Yunnan and Guizhou).
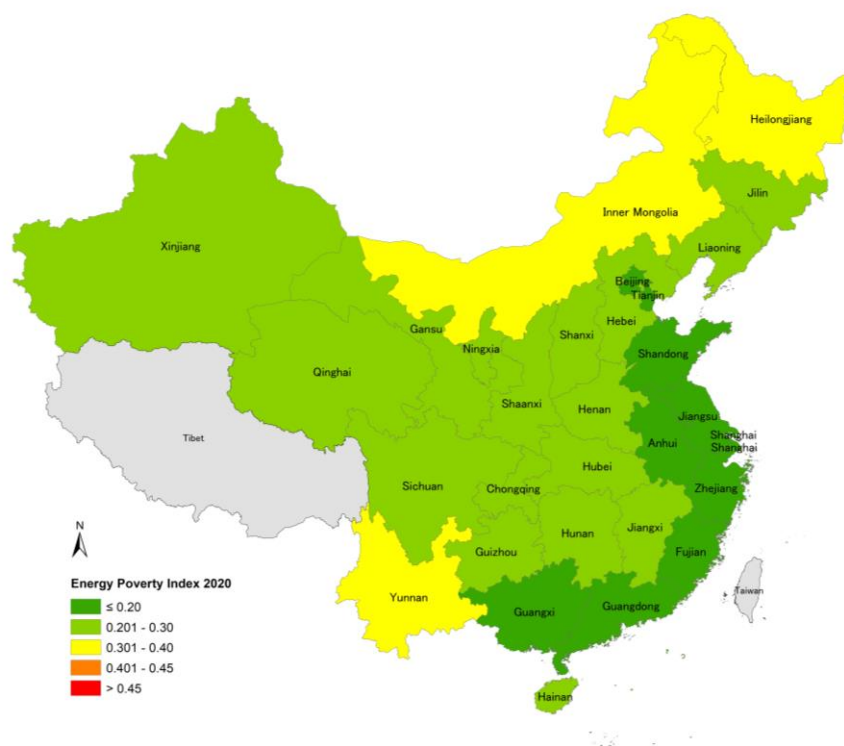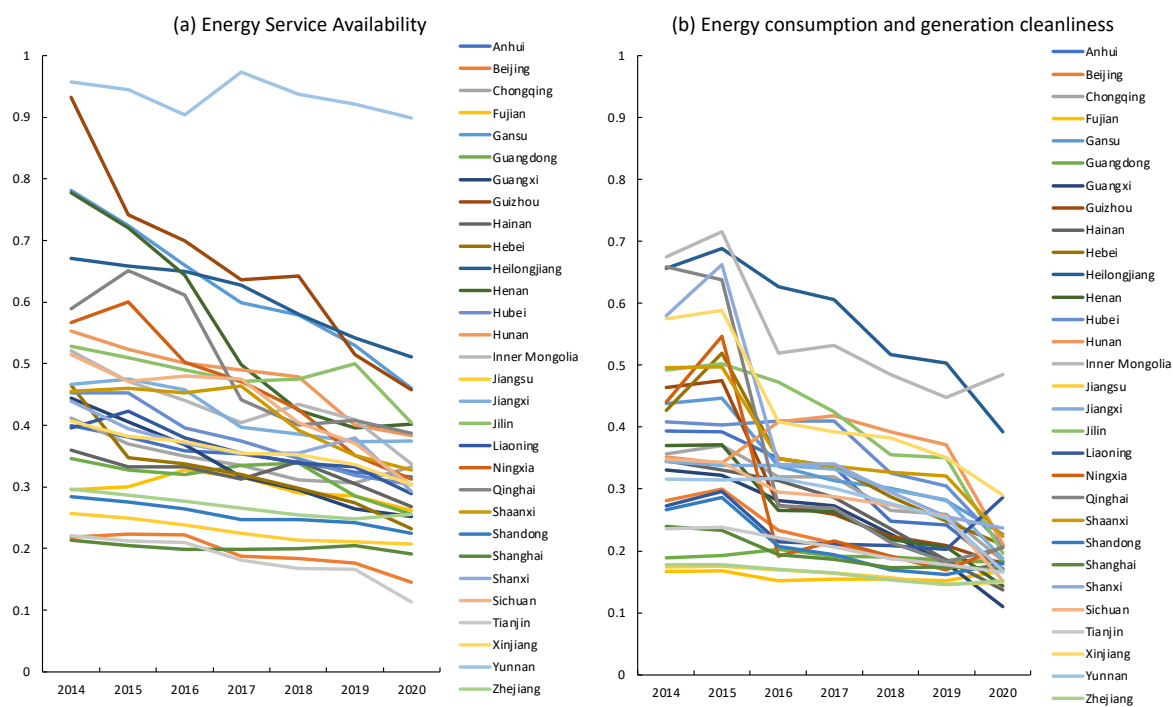
Energy Poverty Index 2016
≤ 0.20
0.201 - 0.30
0.301 - 0.40
0.401 - 0.50
> 0.50

Energy Poverty Index 2017
≤ 0.2
0.201 - 0.30
0.301 - 0.40
0.401 - 0.50
> 0.5

Energy Poverty Index 2018
- ≤ 0.20
- 0.201 - 0.30
- 0.301 - 0.40
- 0.401 - 0.50
- > 0.5

Energy Poverty Index 2019
- ≤ 0.20
- 0.201 - 0.30
- 0.301 - 0.40
- 0.401 - 0.45
- > 0.45

Fig. 13 Distribution of energy poverty in China (2014-2020)

(a) Energy Service Availability

(b) Energy consumption and generation cleanliness

(c) Residential energy affordability

Legend: Anhui, Beijing, Chongqing, Fujian, Gansu, Guangdong, Guangxi, Guizhou, Hainan, Hebei, Heilongjiang, Henan, Hubei, Hunan, Inner Mongolia, Jiangsu, Jiangxi, Jilin, Liaoning, Ningxia, Qinghai, Shaanxi, Shandong, Shanghai, Shanxi, Sichuan, Tianjin, Xinjiang, Yunnan, Zhejiang
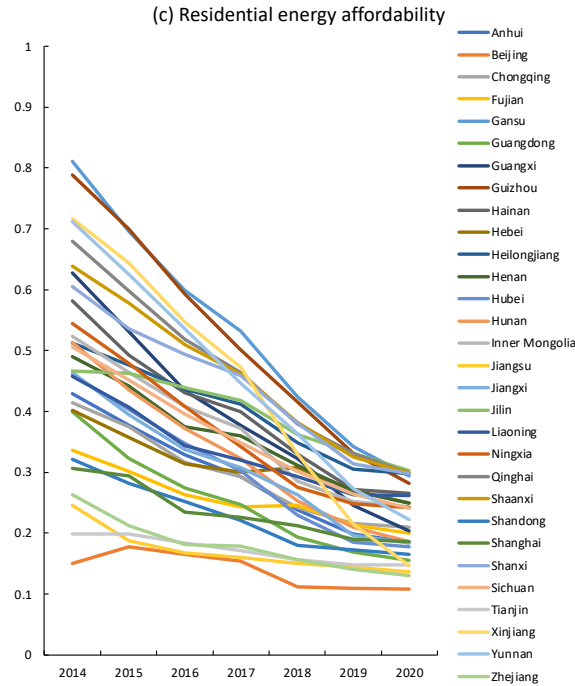
Fig. 14 Provincial energy poverty sub-indices (2014-2020)

Despite the overall downward trend, huge differences exist between the three categories of indices across provinces (Fig. 14), which shows heterogeneity in energy performances. Each province has its own advantages and disadvantages to improve or exacerbate its energy poverty level.

In terms of energy service availability's regional variation, regions like Beijing, Tianjin, and Shanghai show higher energy service availability levels (Fig. 14a), which indicates households there consume more modern energy (e.g., electricity and natural gas) while Yunnan, Guizhou and Gansu Provinces' residents have more difficulties (Fig. 15). The reason could be that, firstly, these economically developed areas have policy support and well-constructed grid power and natural gas supply, while energy supply infrastructure in less-developed areas like Yunnan, Guizhou, etc., are relatively poor. By comparing the energy consumption structure of regions with different levels of economic development, it is found that electricity and gas consumption are higher in regions with more developed economies. The huge difference in the level of economic development may be the main reason for the disparity in the structure of energy consumption. Secondly, there is no winter central heating service for southern provinces like Yunnan, Guizhou, Hunan, and Jiangxi, households' decentralized heating is

inefficient or cannot guarantee residents' needs. For northern regions with central heating systems like Heilongjiang, Gansu, the central heating rate in rural areas is much lower than in urban areas (Fig. 16).
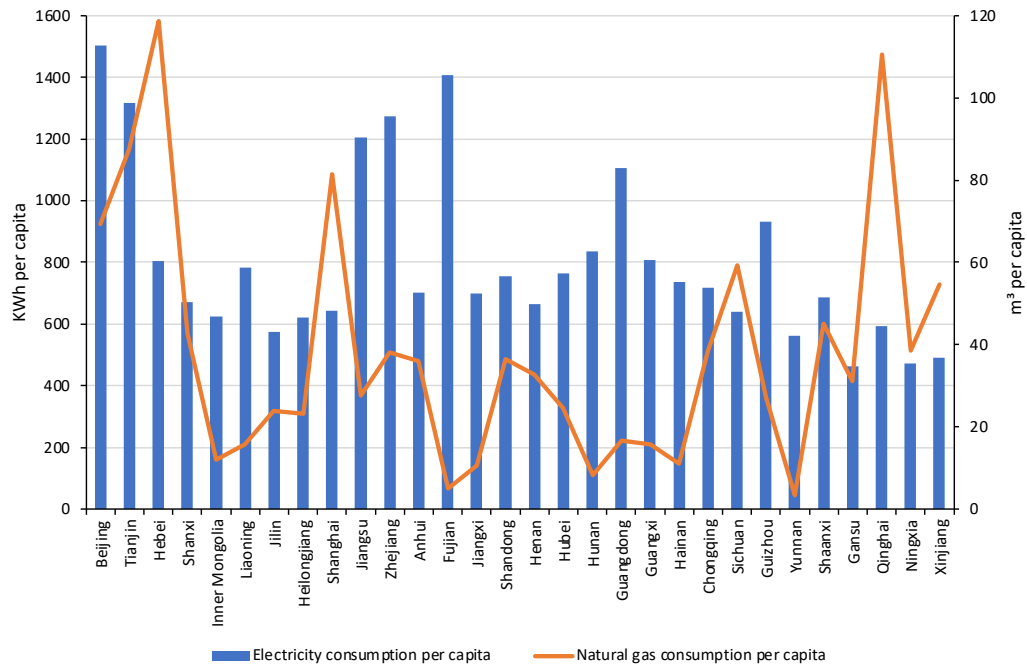

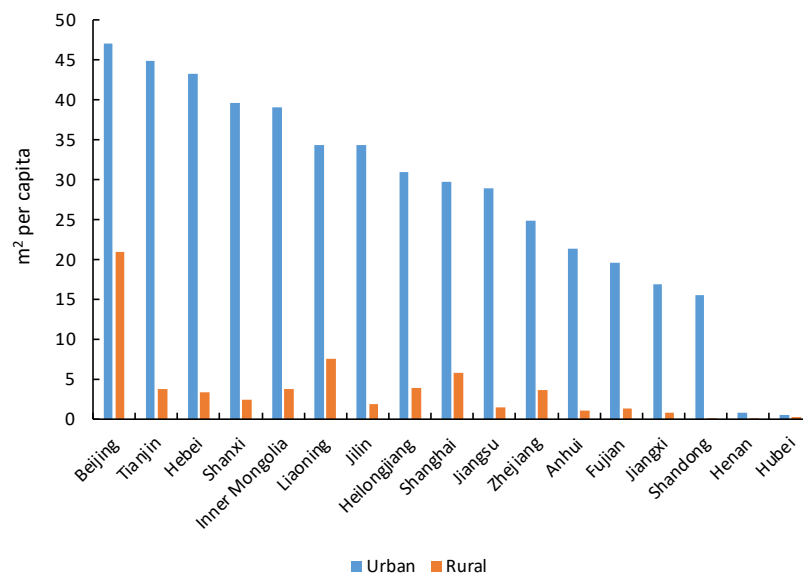Fig. 15 Provincial residents' modern energy consumption (2020)

Fig. 16 Provincial urban and rural residential per capita central heating areas (2020)

For energy supply and consumption cleanliness, decrease of air pollutants from residential energy consumption, non-solid commercial fuel consumption, and non-thermal power generation contribute to this trend. Residential cooking fuels have become modern and cleaner, and those taking straw as primary cooking fuel in poor

areas have declined, clean energy also reduced pollution emissions. There was a sharp decline in many provinces in 2016 (Fig. 14b), this could be due to the government having made unprecedented efforts to reduce air pollutants emissions and energy transition since the 13th Five-Year Plan, thus energy cleanliness in all sectors including residential has been dramatically improved. Fig. 17 shows changes in SO_2, NOx and Particulate Matter emissions during the study period, SO_2 emissions have dropped significantly, except for Hunan Province; NOx and PM emission also indicates a declining trend in most provinces. Ningxia and Guizhou have the highest ratio of non-solid commercial fuel consumption, and Yunnan and Qinghai have the cleanest power generation structure (Fig. 18), this is also the reason why the provinces with more significant improvement in energy poverty during the study period are Qinghai, Ningxia, and Guizhou, despite of their poor energy service availability level. It is shown in Fig. 19 that the different types of renewable energy generation from 2014-2020, with varying endowments of resources in different provinces. For instance, Sichuan and Yunnan are the richest in hydraulic resources, Inner Mongolia and Xinjiang are the largest wind power provinces, while Solar power production in Hebei and Shandong is growing very fast.
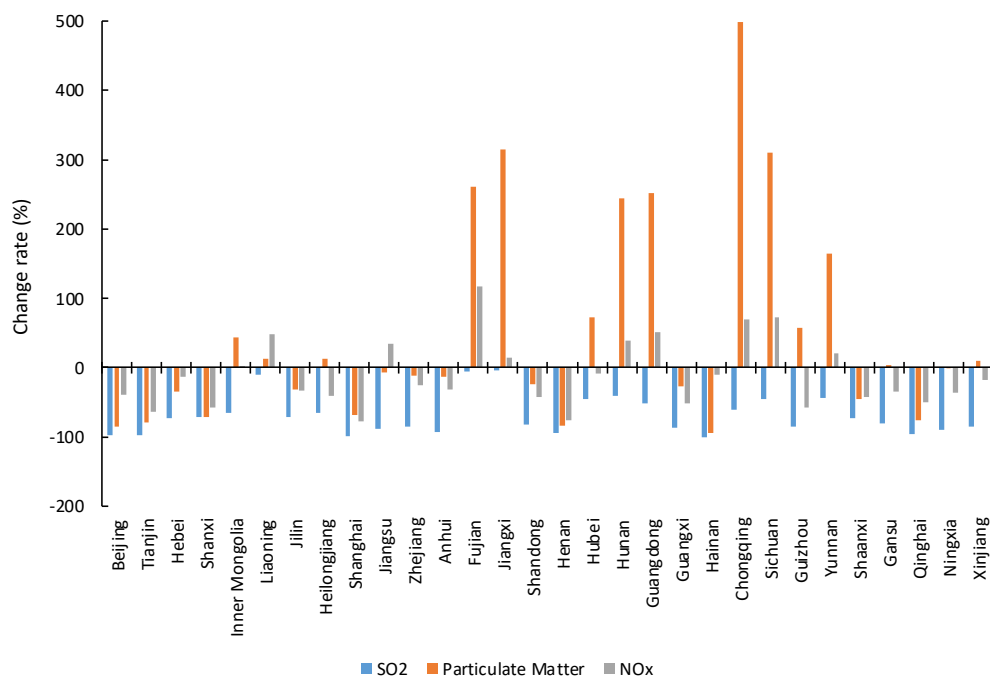

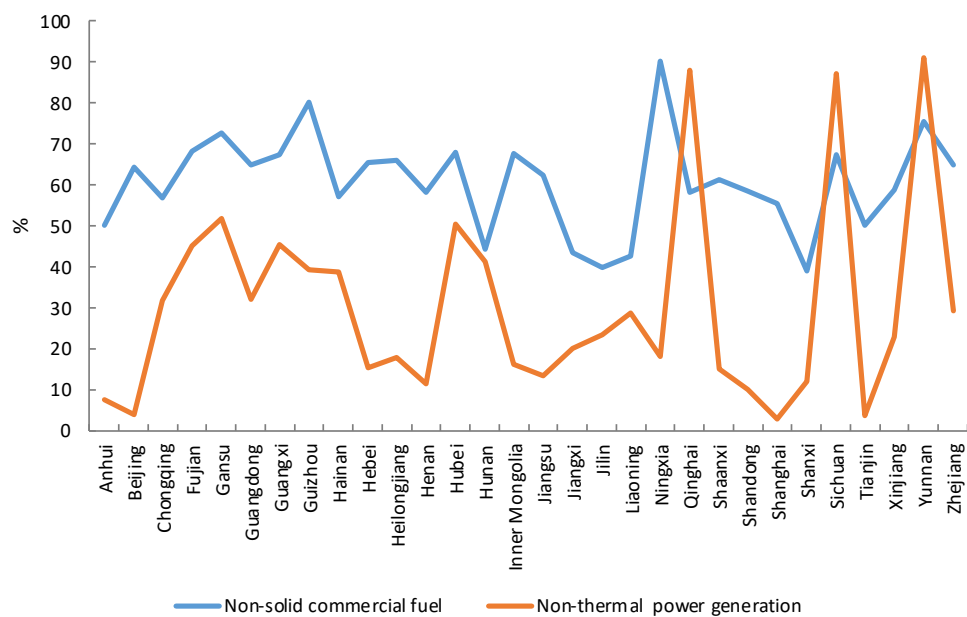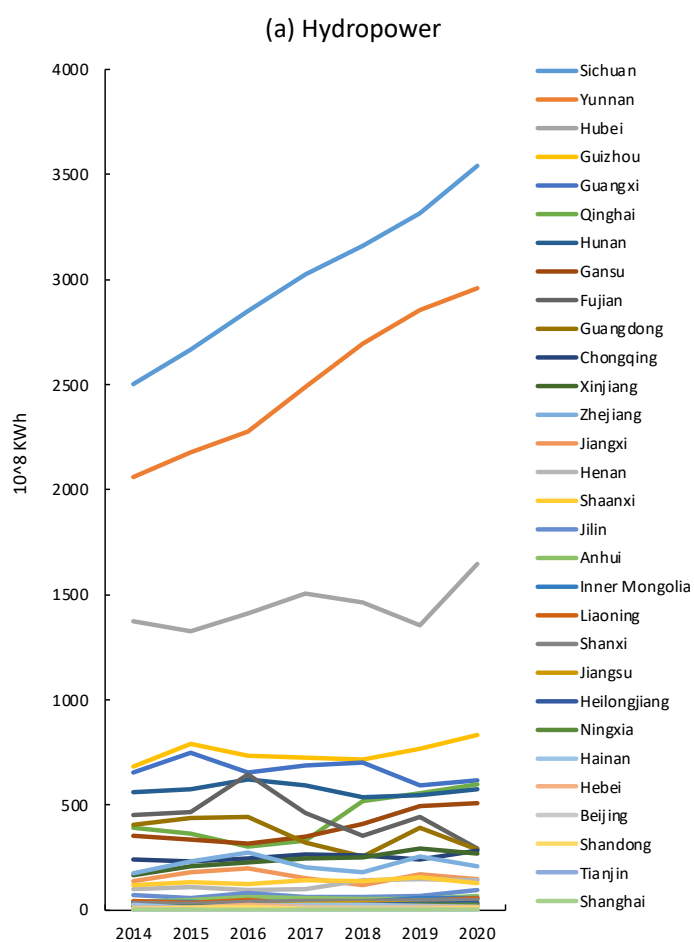Fig. 17 Changes of air pollutants emissions from the residential source (2014-2020)

Fig. 18 Provincial average clean energy structure (2020)
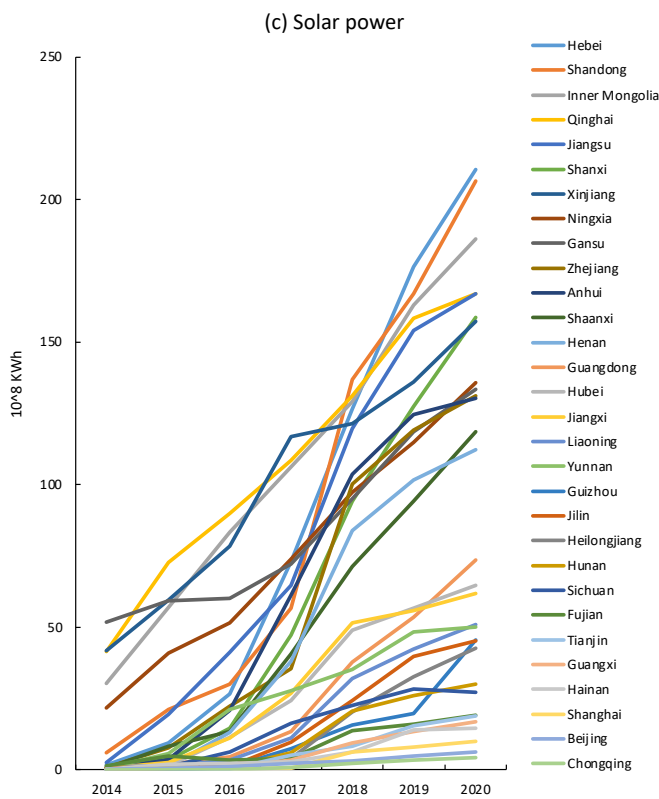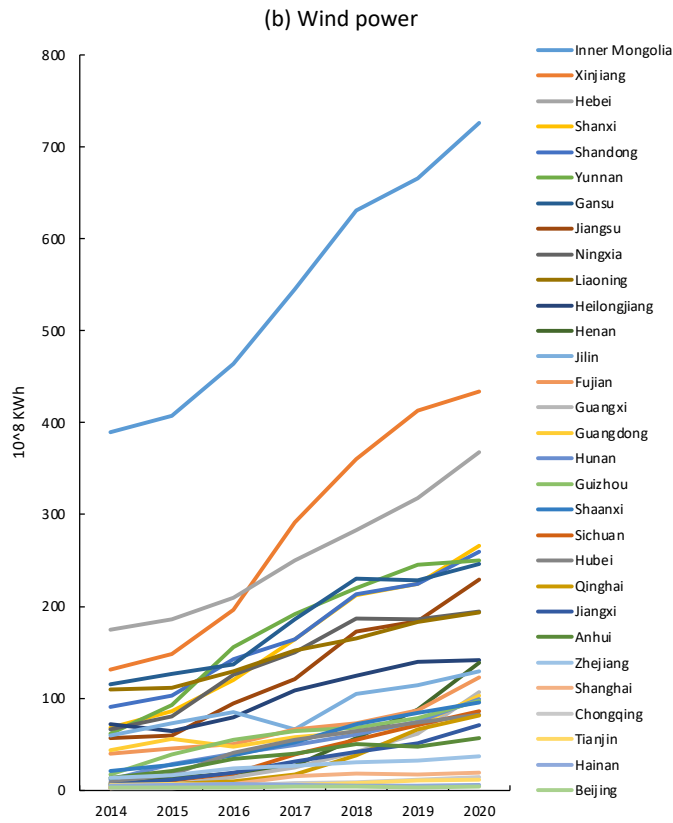
(a) Hydropower

Fig. 19 Power generation by renewable energy sources (2014-2020)

In terms of household energy affordability and efficiency, the southeastern coastal areas, like Zhejiang, Jiangsu, and Shanghai, have the best performance, while northwest and

southwest regions have higher indices (Fig. 14c), indicating the correlation between social-economic development and energy poverty. The energy intensity of most provinces also shows decreasing trend during the past six years (Fig. 20). In recent years, poverty alleviation efforts have increased, and the incidence of rural poverty has been decreased year by year (Fig. 21). Meanwhile, photovoltaic poverty alleviation is in line with other two national strategies: the precise poverty alleviation strategy and the clean and low-carbon energy development strategy, which has received policy support but is still at a low development level now, with the barriers like insufficient infrastructure and subsidy delays (Li et al. 2018).
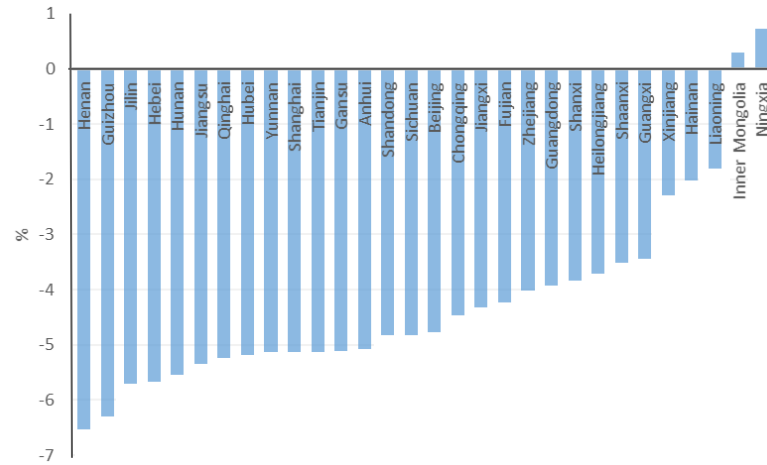

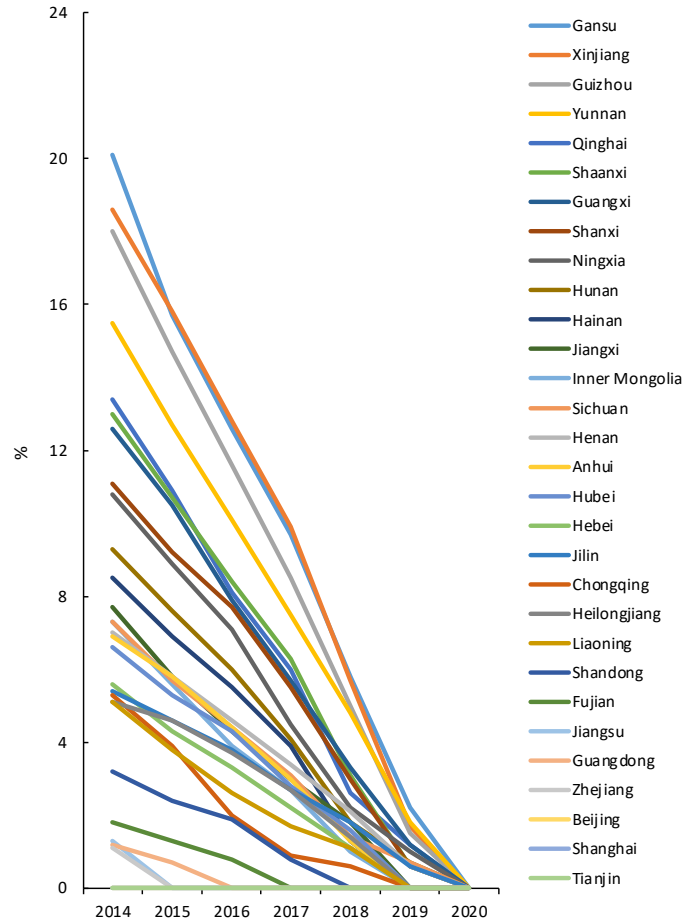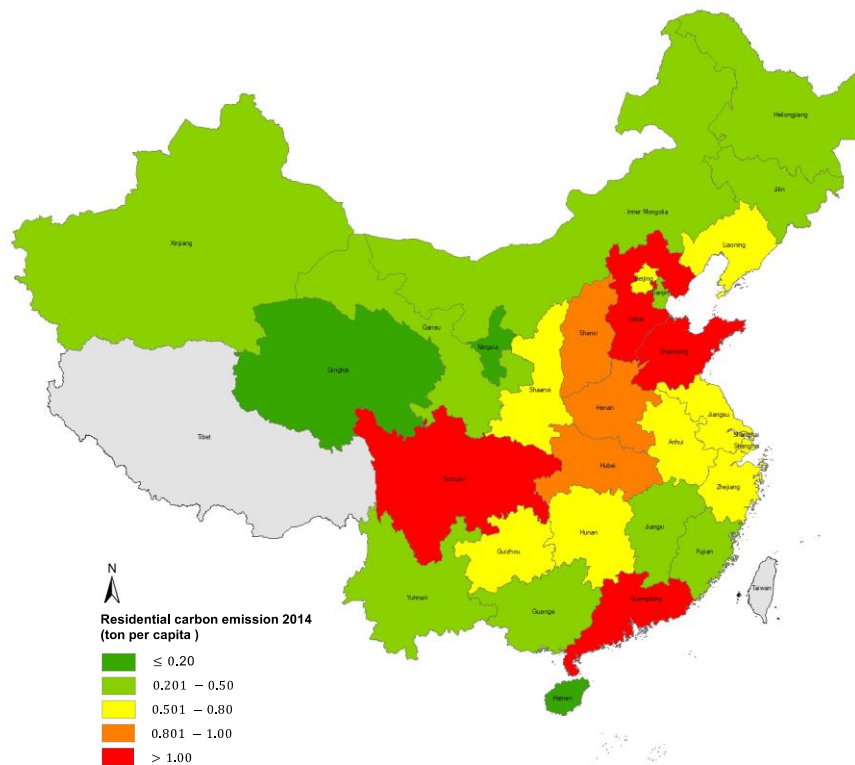Fig. 20 Average change in energy consumption of 10,000 yuan of regional GDP (2014 to 2020)

Fig. 21 Incidence of poverty in rural areas (2014-2019)

4.2 Carbon emissions from household energy consumption

Fig. 22 shows the carbon emission from household energy consumption from 2014 to 2020, it can be seen that the carbon emissions of all provinces show an increasing trend, and there are obvious regional differences in per capita emissions. The central and eastern regions have large carbon emissions, while the northern and southwestern regions are relatively small. Energy poverty level can also be corroborated with the per capita carbon emissions from domestic sources in each province. According to Chakravarty & Tavoni (2013), energy poverty alleviation will increase energy consumption, thus increasing carbon emissions. The analysis in this paper reveals that energy poverty is relatively high in the northeast, north and southwest regions, which are also the regions with lower per capita carbon emissions in China at present. The central and southeast coastal regions have a smaller energy poverty index but high per

capita carbon emissions. Thus, the energy poverty level is currently negatively correlated with carbon emissions in China. This can also be explained by the fact that areas with high levels of energy poverty have relatively less residential energy consumption.

Residential carbon emission 2014 (ton per capita)

- ≤ 0.20
- 0.201 − 0.50
- 0.501 − 0.80
- 0.801 − 1.00
- \> 1.00

**Residential carbon emission 2015
(ton per capita)**

- ≤ 0.20
- 0.201 − 0.50
- 0.501 − 0.80
- 0.801 − 1.00
- \> 1.00

**Residential carbon emission 2016
(ton per capita)**

- ≤ 0.20
- 0.201 − 0.50
- 0.501 − 0.80
- 0.801 − 1.00
- \> 1.00

Residential carbon emission 2017 (ton per capita)

≤ 0.20
0.201 — 0.50
0.501 — 0.80
0.801 — 1.00
> 1.00

Residential carbon emission 2018 (ton per capita)

≤ 0.20
0.201 — 0.50
0.501 — 0.80
0.801 — 1.00
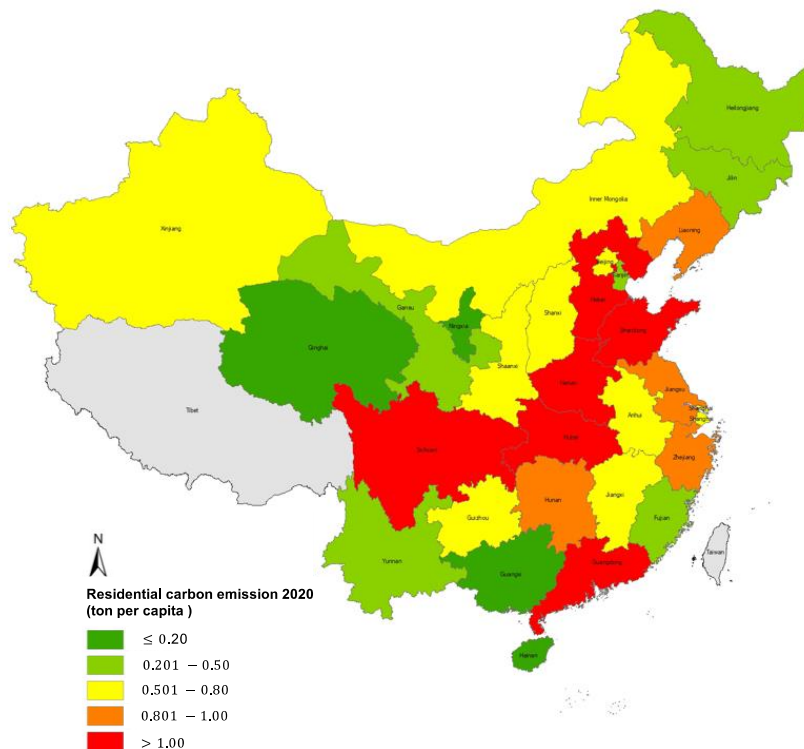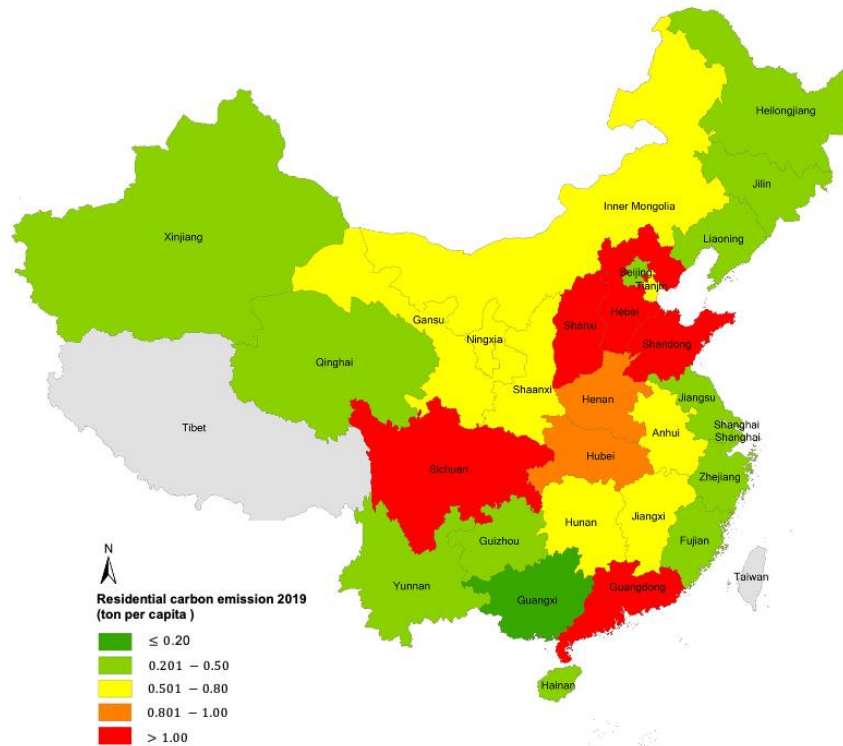> 1.00

Fig. 22 Provincial carbon emission per capita (2014-2020)

However, in the context of SDGs and 'just transition', poverty alleviation along with the green and low-carbon energy development strategy are significant in China and worldwide. Thus, the link between energy poverty and processed systemic change in energy transformation and the carbon sector and the intersection between energy

poverty policy and climate change policy is essential.

4.3 Scenarios Outlook

4.3.1 Business as Usual (BAU)

Energy poverty level shows a continued downward trend in the BAU scenario across the country from 2021 to 2035 (Fig. 23). As for the spatial distribution, the northern area shows obviously higher energy poverty index than the southern area of China, Heilongjiang and Inner Mongolia continue to show the highest energy poverty level, while Beijing, Tianjin and eastern coastal area are the least energy deprived (Fig. 24). And urban area still shows better energy poverty situation than rural area (Fig. 25).

However, when it comes to the total household carbon emission of each province, there will be a continuous growth along the time from 2021-2035 (Fig. 26), so the per capita emission (Fig. 28), which is inconsistent with the Chinese government's current goal of energy efficiency and carbon reduction. Carbon emission from urban household is much higher than it from rural energy consumption, and the difference is increasing by year (Fig. 27). Hebei, Shandong, Liaoning and Inner Mongolia are the biggest residential carbon emission emitters nationwide, due to the heavier energy structure.
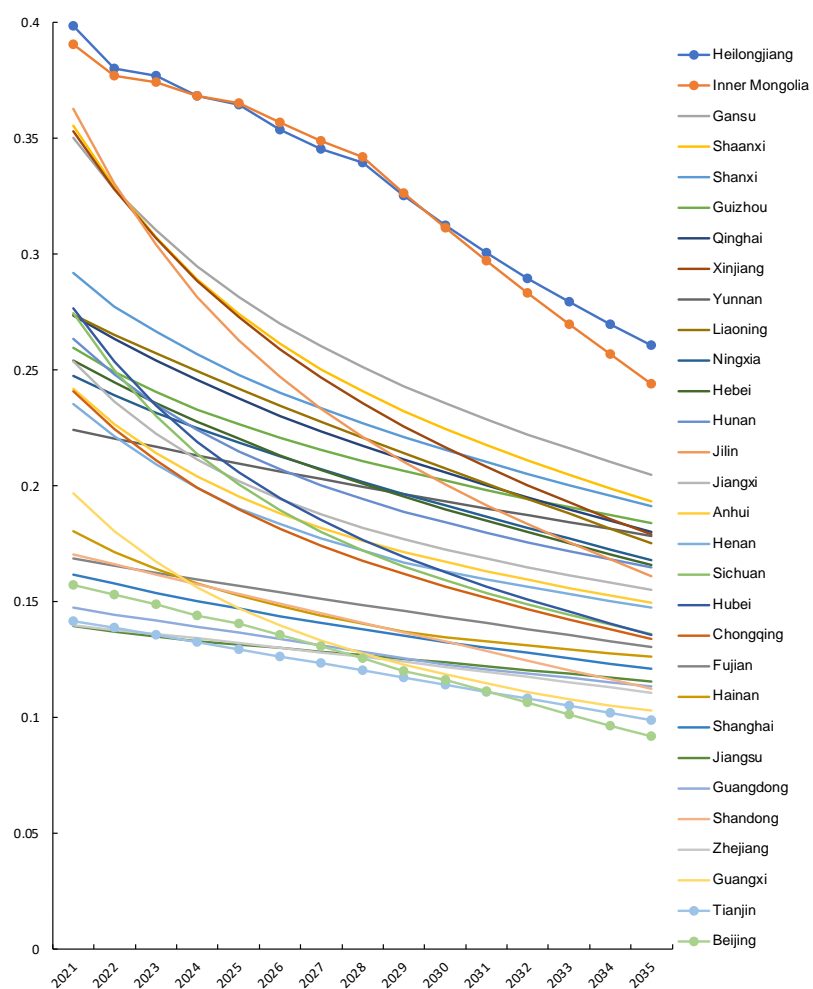
Fig. 23 Energy poverty index by BAU (2021-2035)
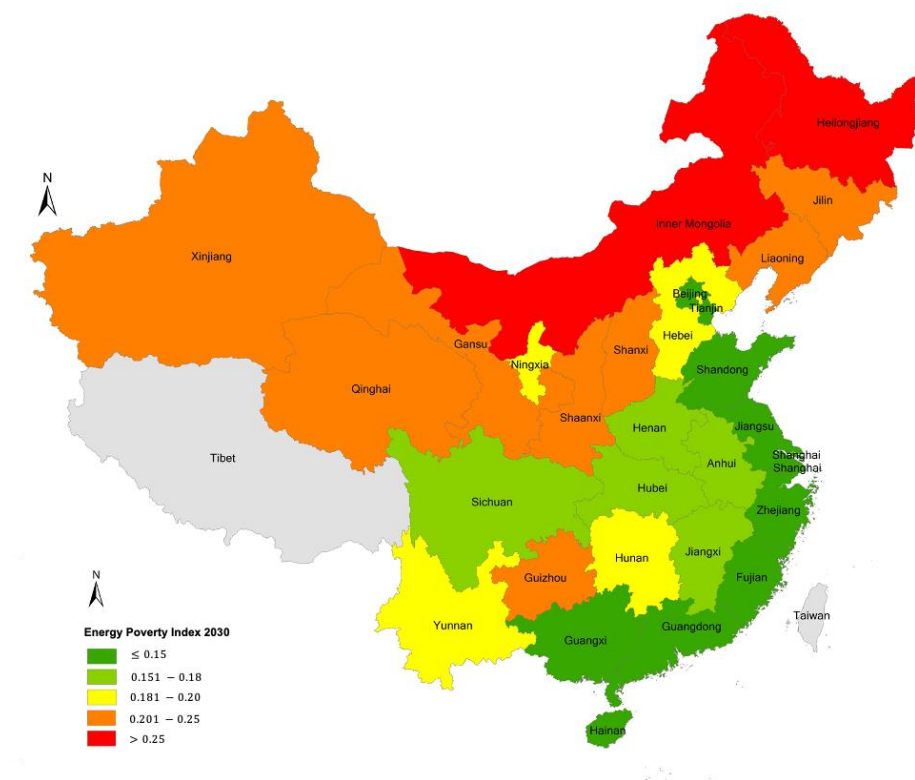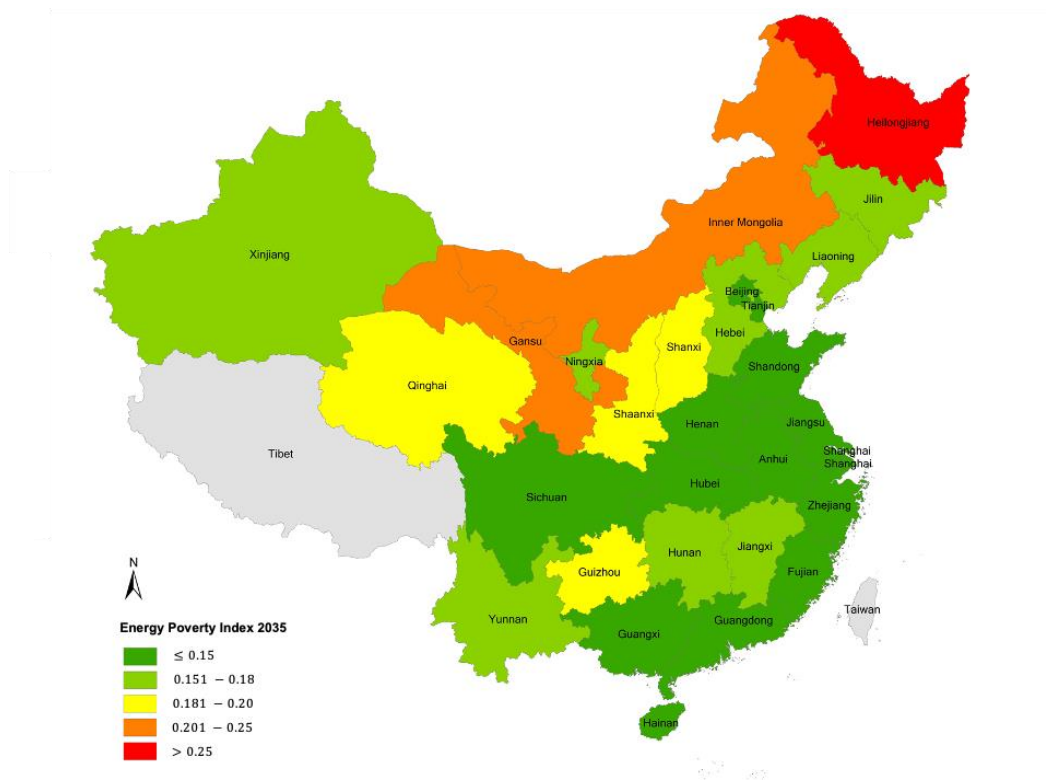
Fig. 24 Distribution of EPI by BAU (2030&2035)
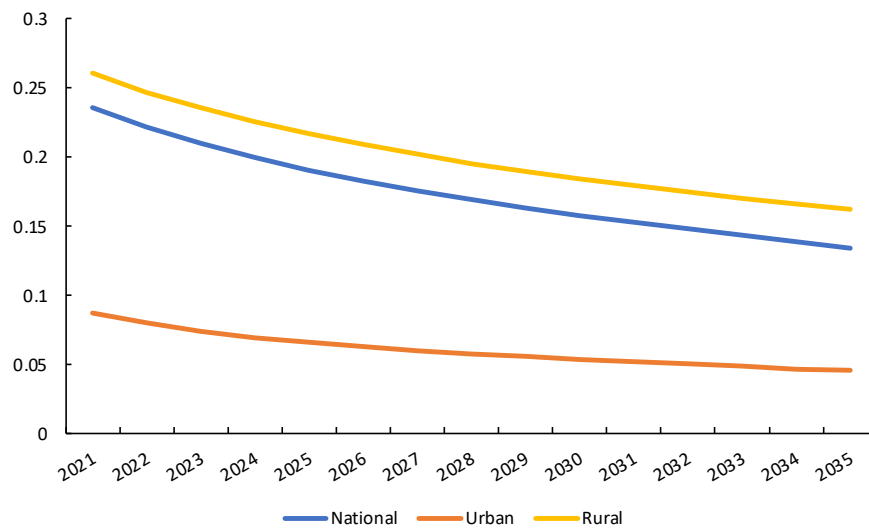
Fig. 25 Urban and Rural Average EPI by BAU (2021-2035)
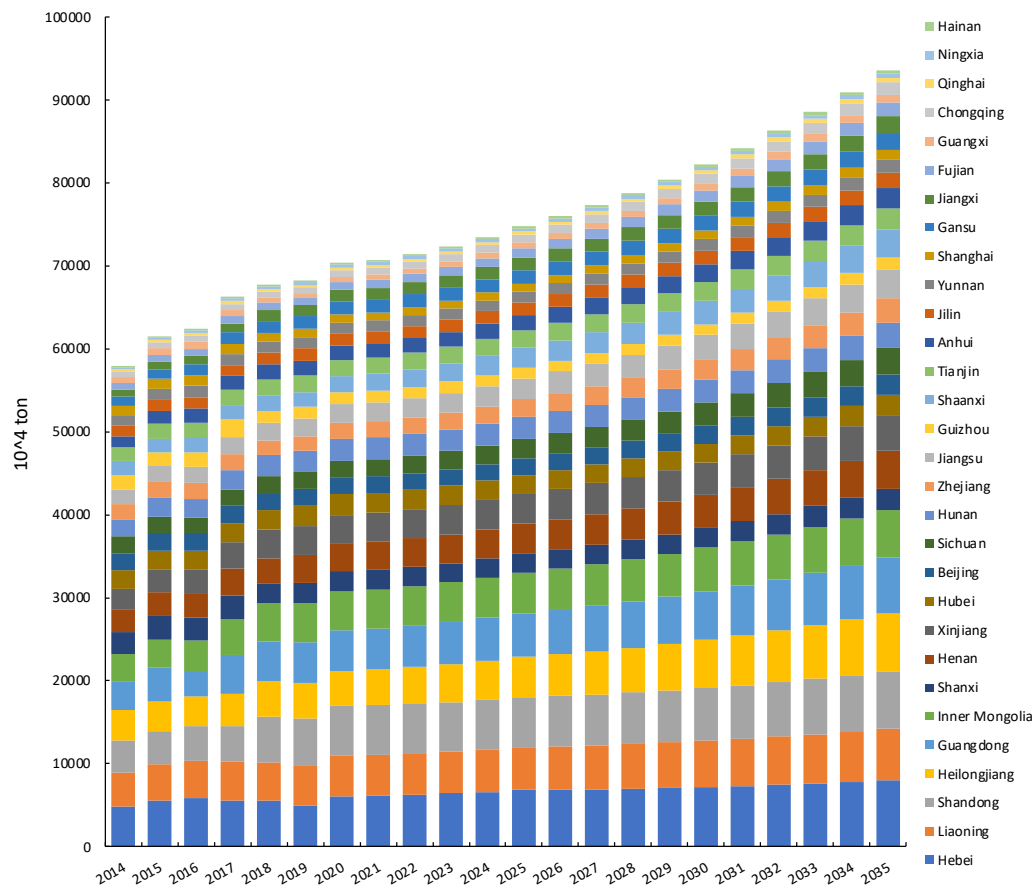
Fig. 26 Household total emission by BAU (2021-2035)

Fig. 27 Total carbon emission by urban and rural household (BAU)
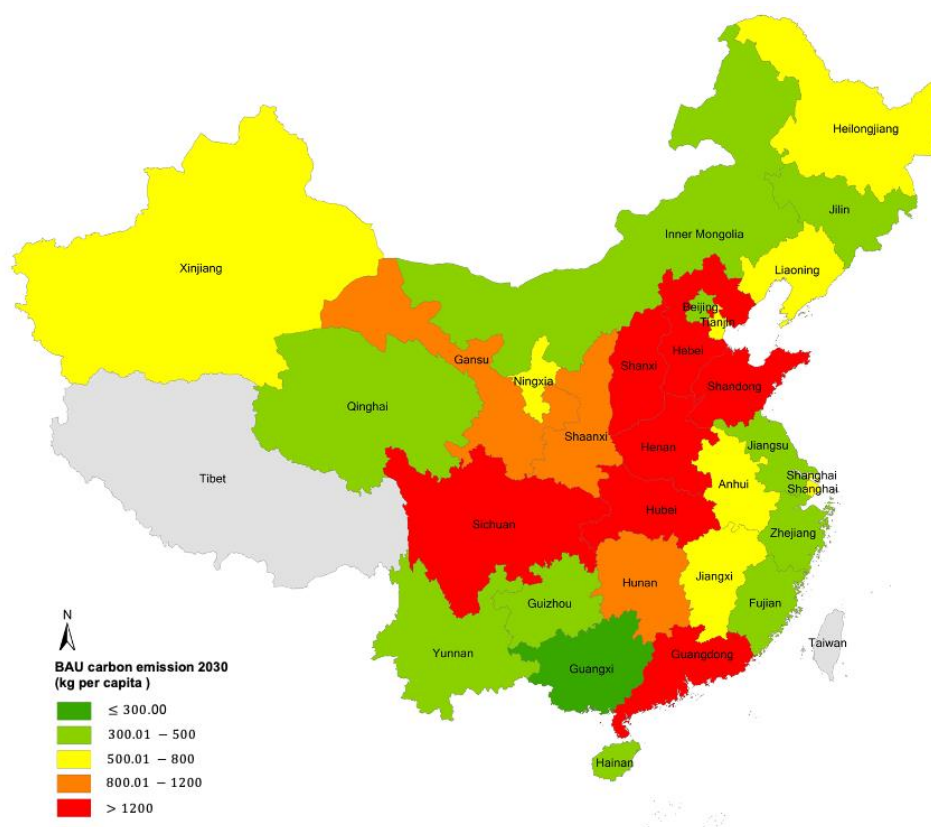
Fig. 28 Provincial carbon emission per capita by BAU (2030 & 2035)

4.3.2　Carbon emission reduction (CER)

The EPI also experiences a downward trend (Fig. 29), and the trend for urban-rural and regional differences closely mirrors the trajectory observed in the BAU scenario (Fig. 30 & Fig. 31). Total household carbon emissions of each province consistently decrease over the period from 2021 to 2035 under the CER scenario (Fig. 32). Simultaneously, the per capita carbon emissions within each province also demonstrate a downward trajectory during the same time frame (Fig. 34). This gradual reduction indicates a positive environmental trend and a commitment to less energy consumption and sustainable practices. Carbon emissions from both urban and rural sources exhibit a similar pattern to that of the BAU scenario (Fig. 33). Despite the overall decline in household emissions, these sectors still face challenges in effectively curbing their carbon footprint.

Fig. 29 Energy poverty index by CER (2021-2035)
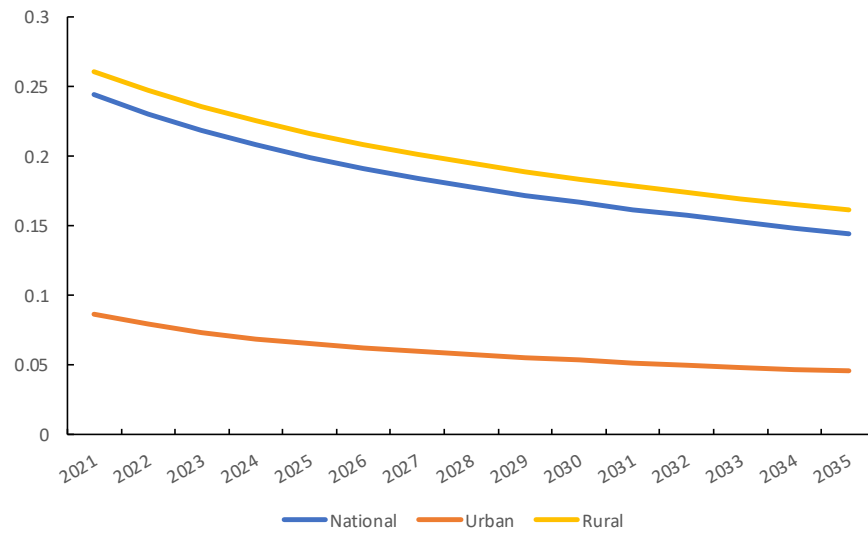
Fig. 30 Urban and Rural Average EPI by CER (2021-2035)
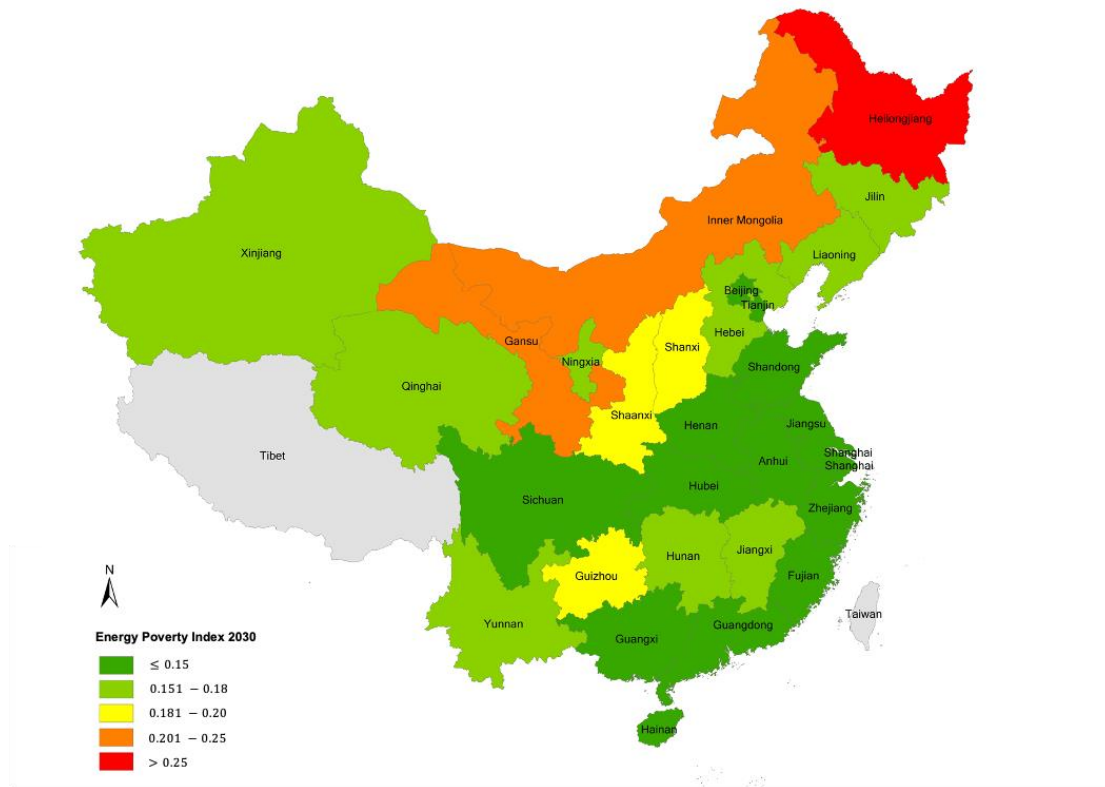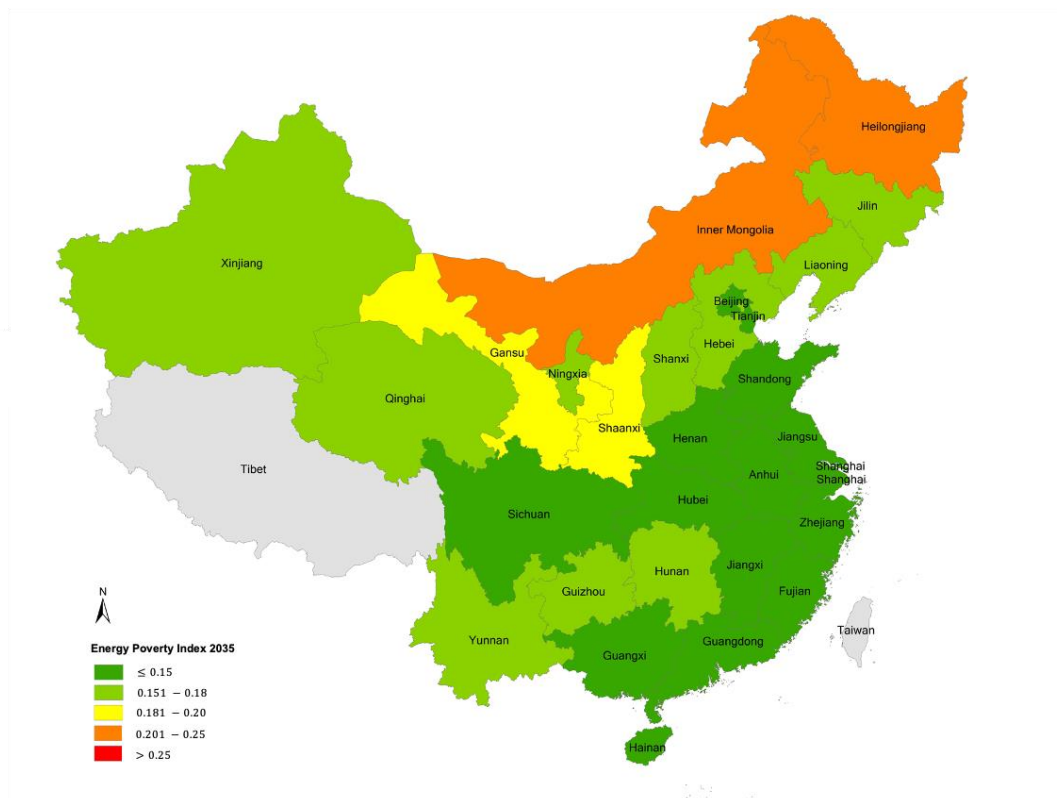
Fig. 31 Distribution of EPI by CER (2030&2035)
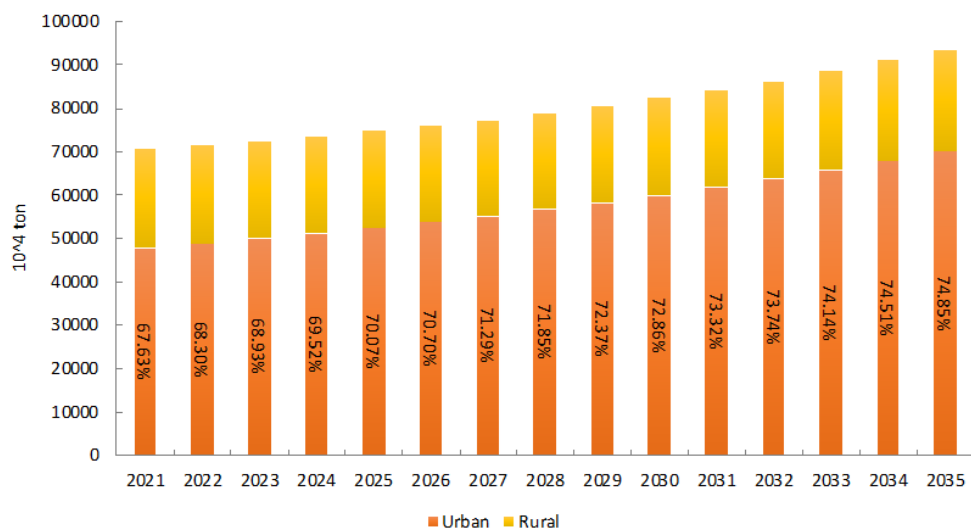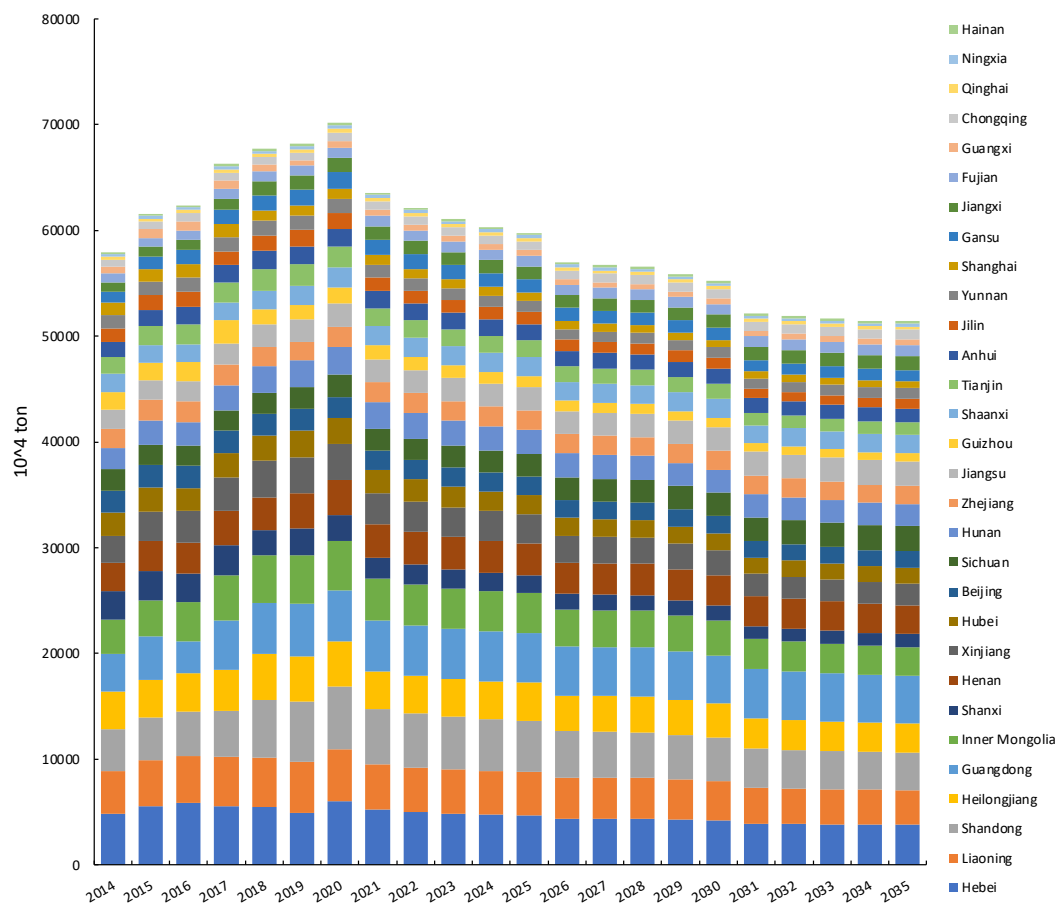

Fig. 32 Household total emission by CER (2021-2035)

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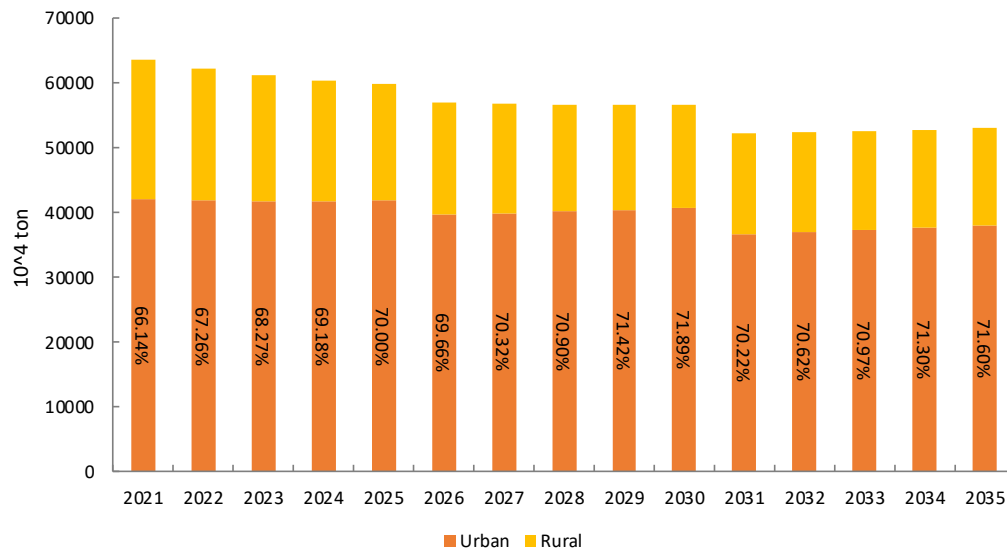
Fig. 33 Total carbon emission by urban and rural households (CER)
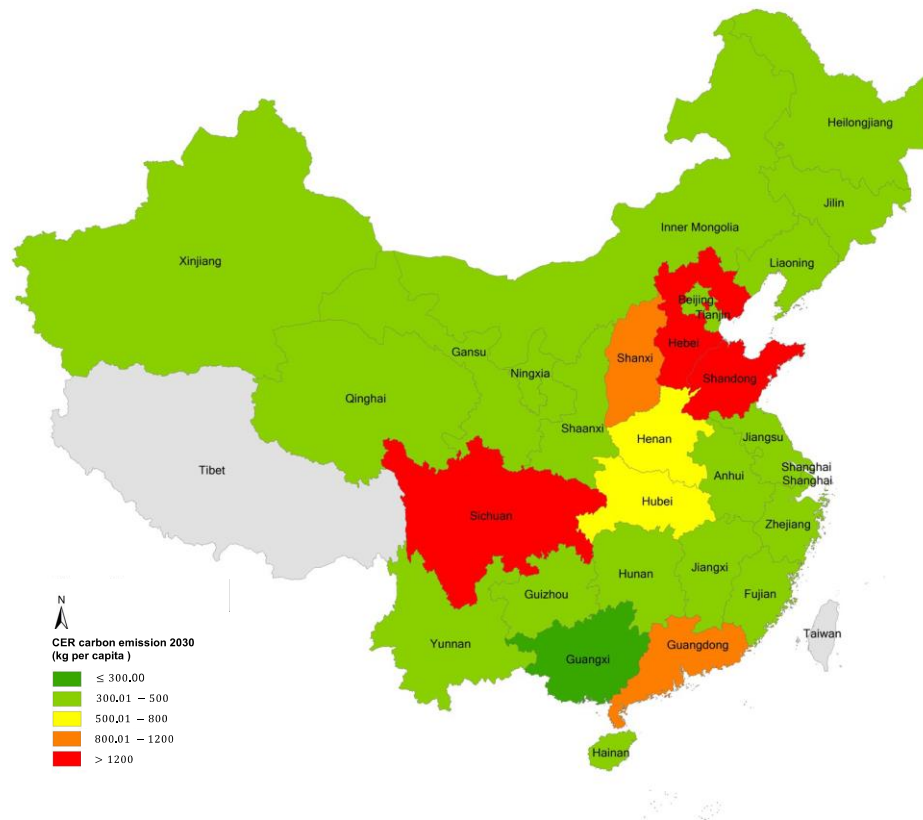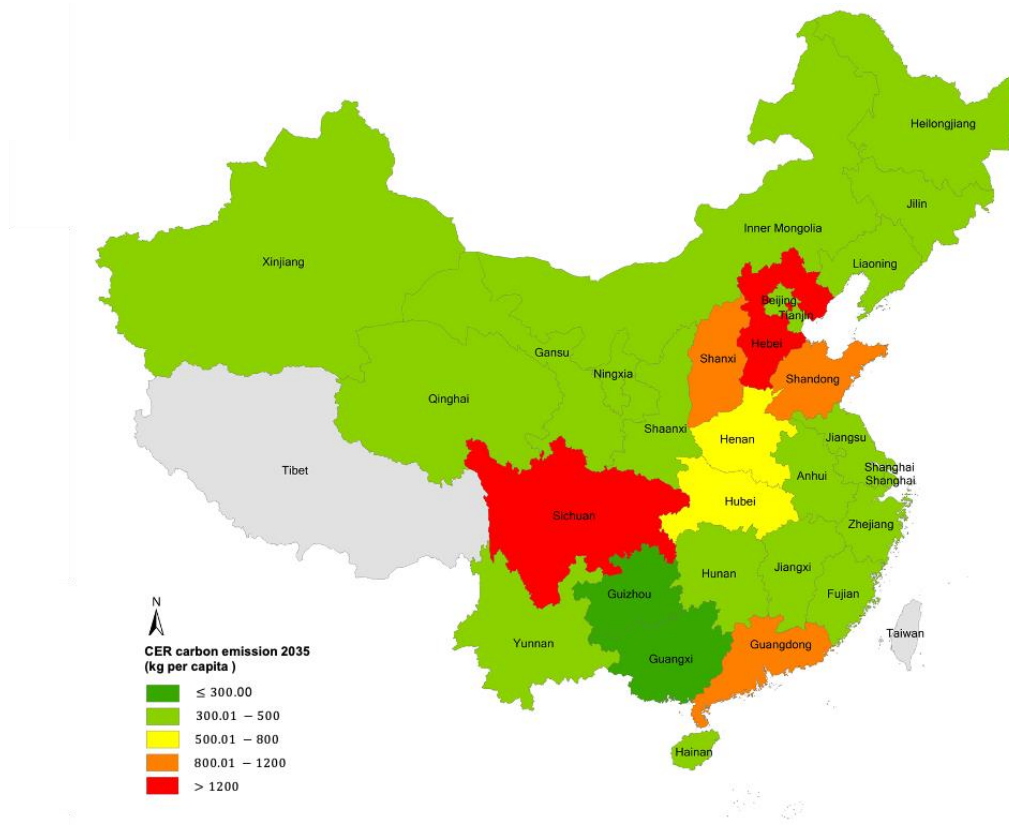
Fig. 34 Provincial carbon emission per capita by CER (2030 & 2035)

4.3.3 Renewable Energy (REN)

The REN scenario projects that solar photovoltaic (PV), wind, and hydroelectric power will play a predominant role in generating electricity from renewable sources. These clean energy technologies are expected to contribute significantly to the overall renewable energy mix, highlighting the shift towards sustainable power generation. Examining the period from 2021 to 2035 under the REN scenario, it is evident that the total household carbon emissions in each province show a consistent decrease over time (Fig. 38). This decline reflects the successful implementation of renewable energy sources and energy-efficient practices, contributing to a greener and more sustainable environment. Notably, despite the decreasing trend in total household carbon emissions, urban households still account for most carbon emissions arising from residential activities (Fig. 39). This emphasizes the need for targeted interventions and sustainable practices specifically tailored for urban areas to address the challenges associated with reducing carbon footprints in densely populated regions. EPI displays a sharper

declining trend (Fig. 35). This indicates significant progress in addressing energy poverty and improving access to clean and affordable modern energy sources. The emphasis placed on reducing energy poverty under the REN scenario is evident in the more pronounced downward trajectory of the EPI, reflecting efforts to ensure equitable access to clean and reliable energy for all.
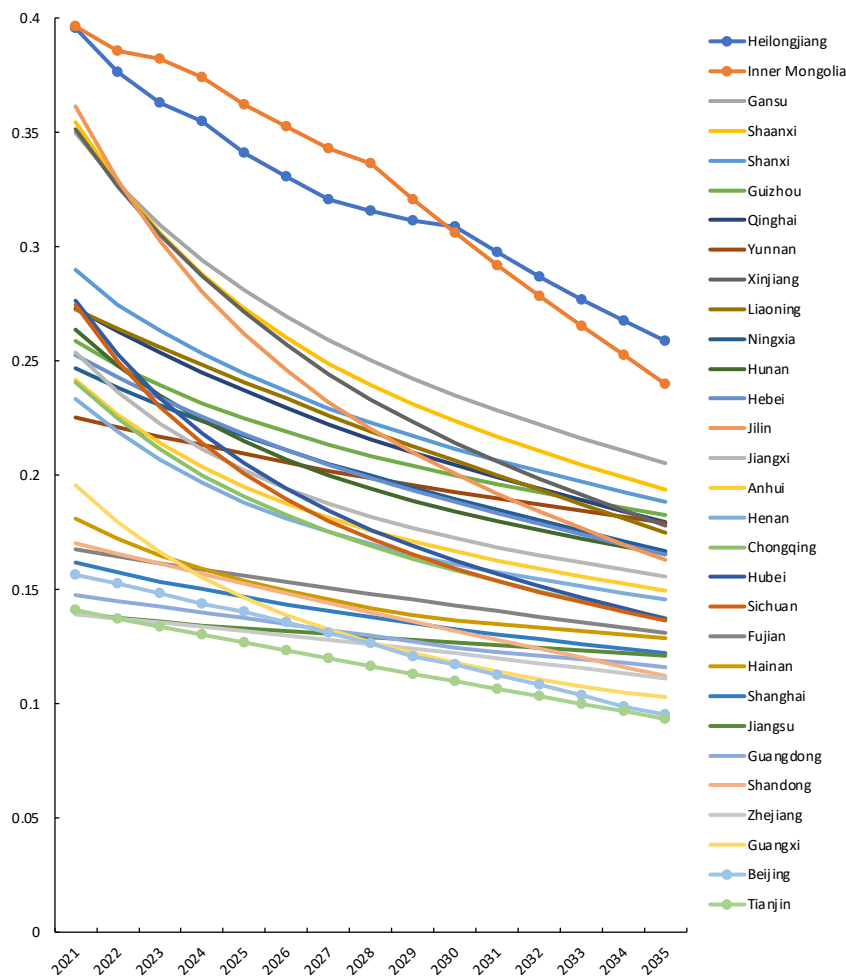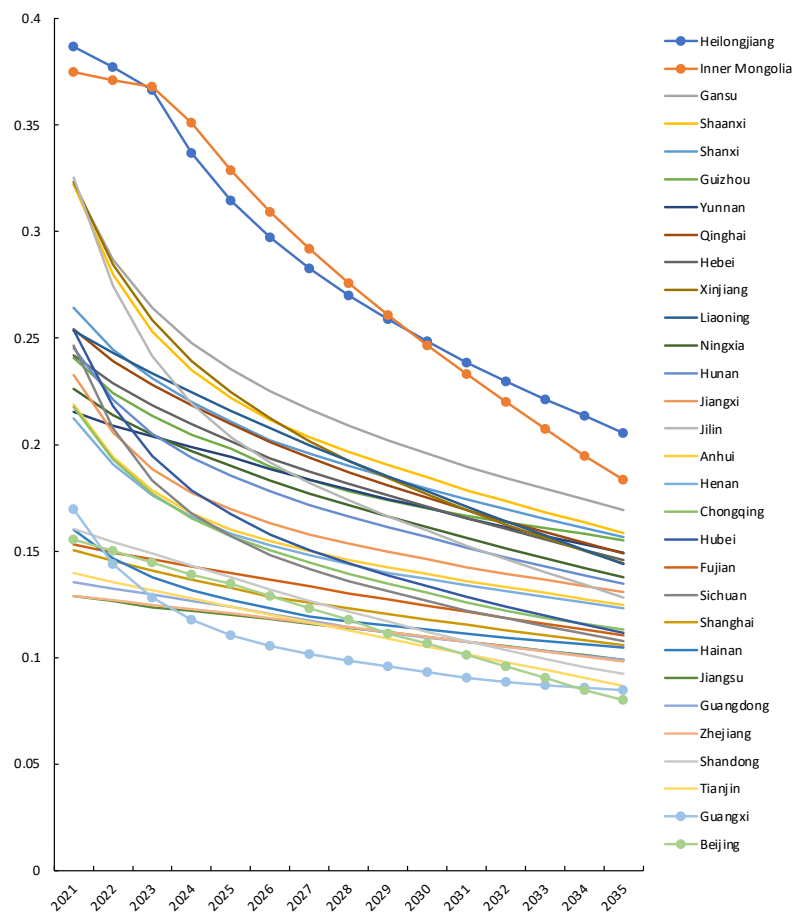

Fig. 35 Energy poverty index by REN (2021-2035)
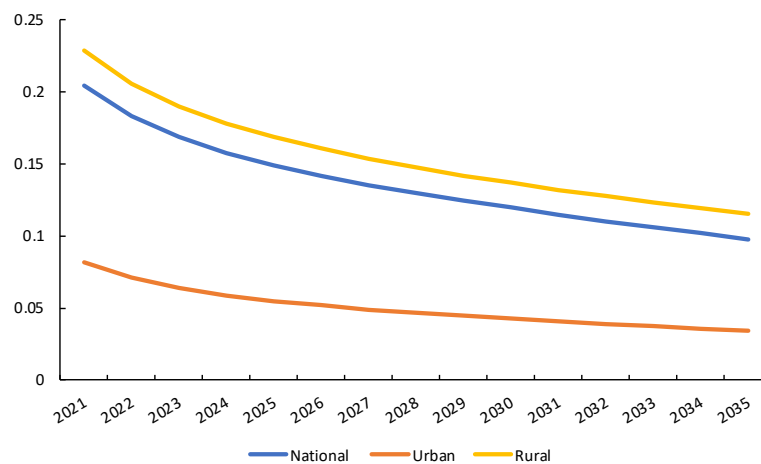
Fig. 36 Urban and Rural Average EPI by REN (2021-2035)
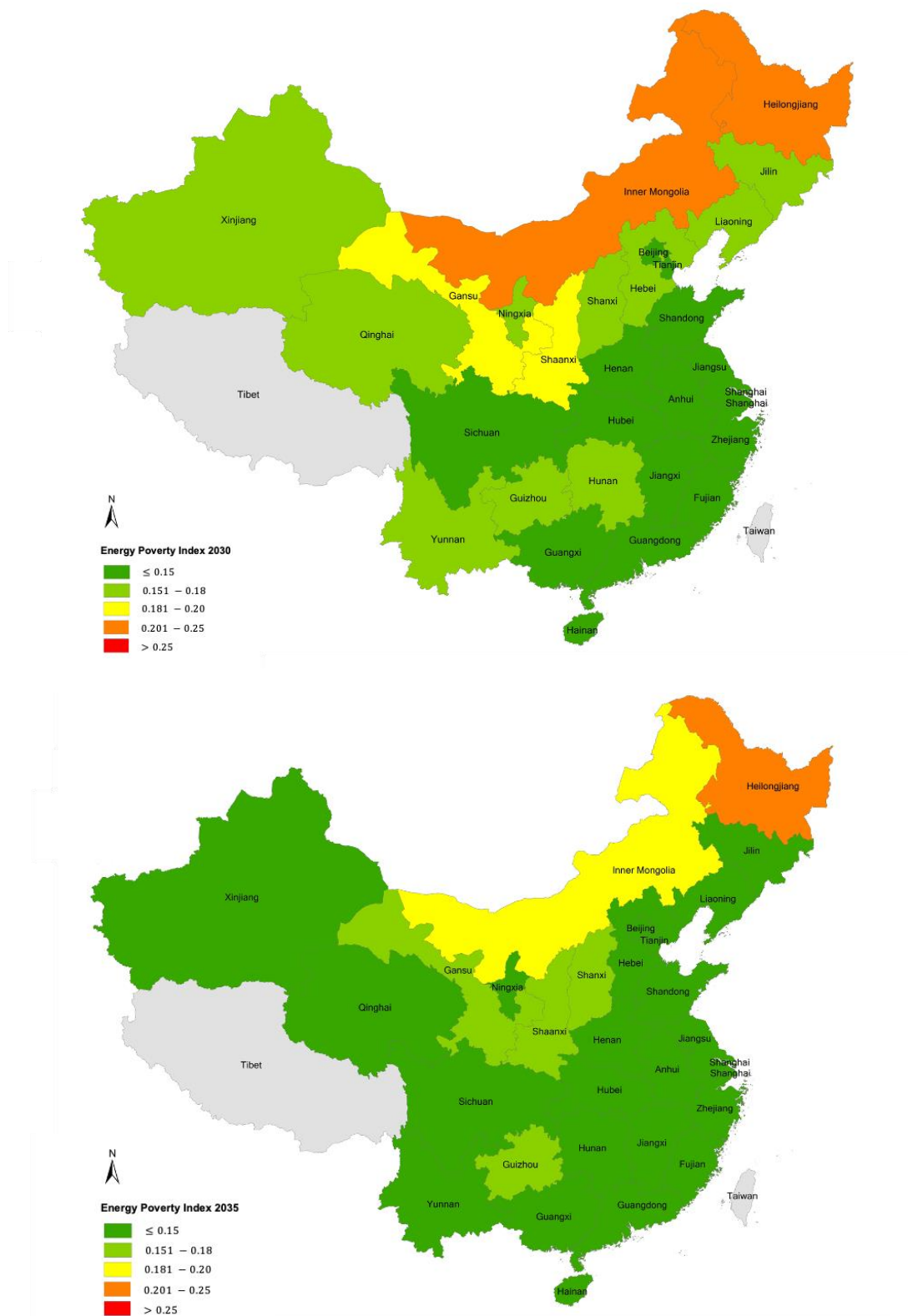
Fig. 37 Distribution of EPI by REN (2030&2035)
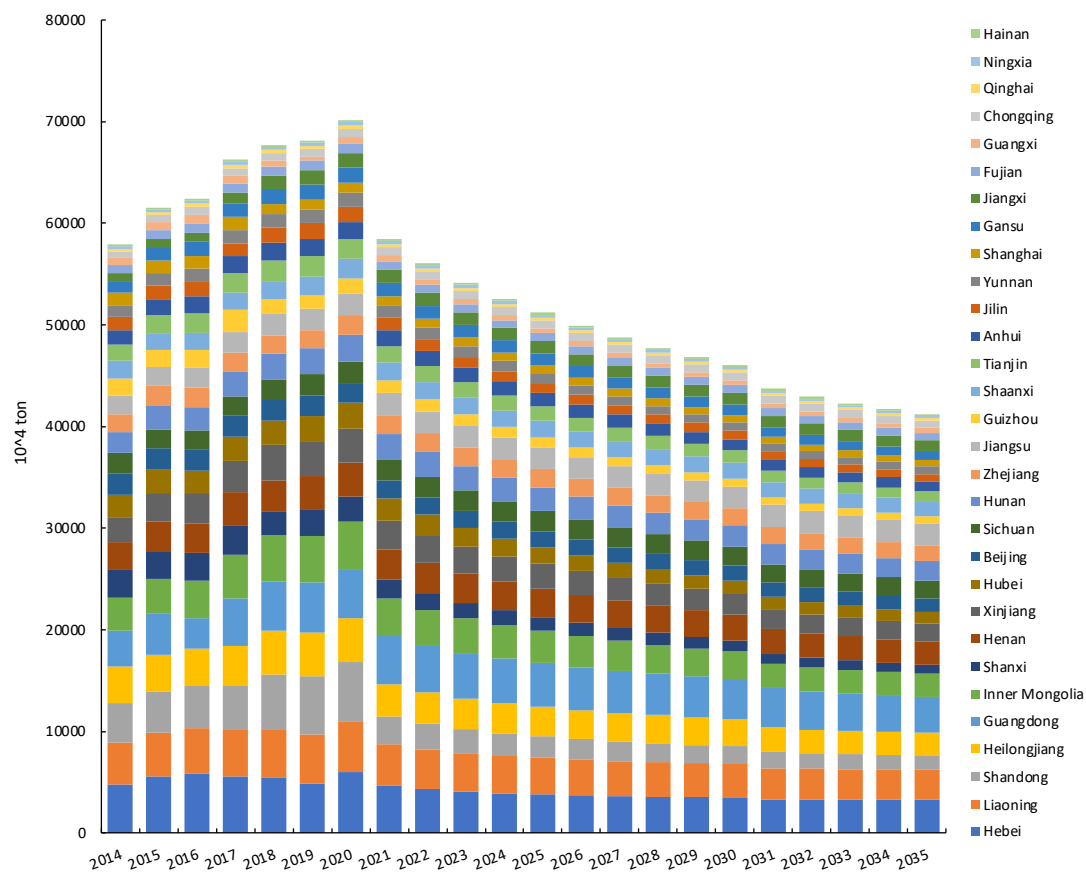
Fig. 38 Household total emission by REN (2021-2035)
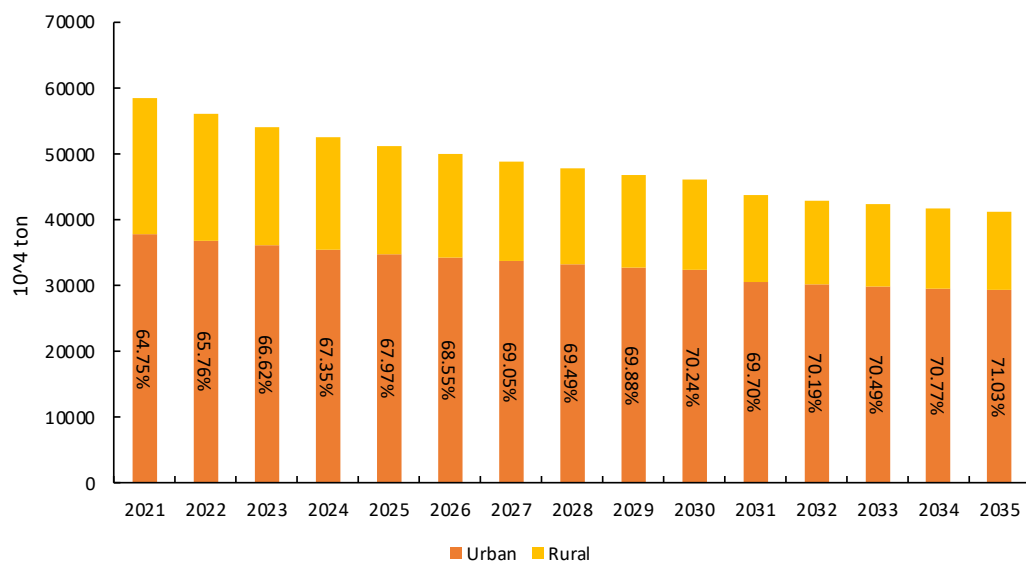
Fig. 39 Total carbon emission by urban and rural household (REN)
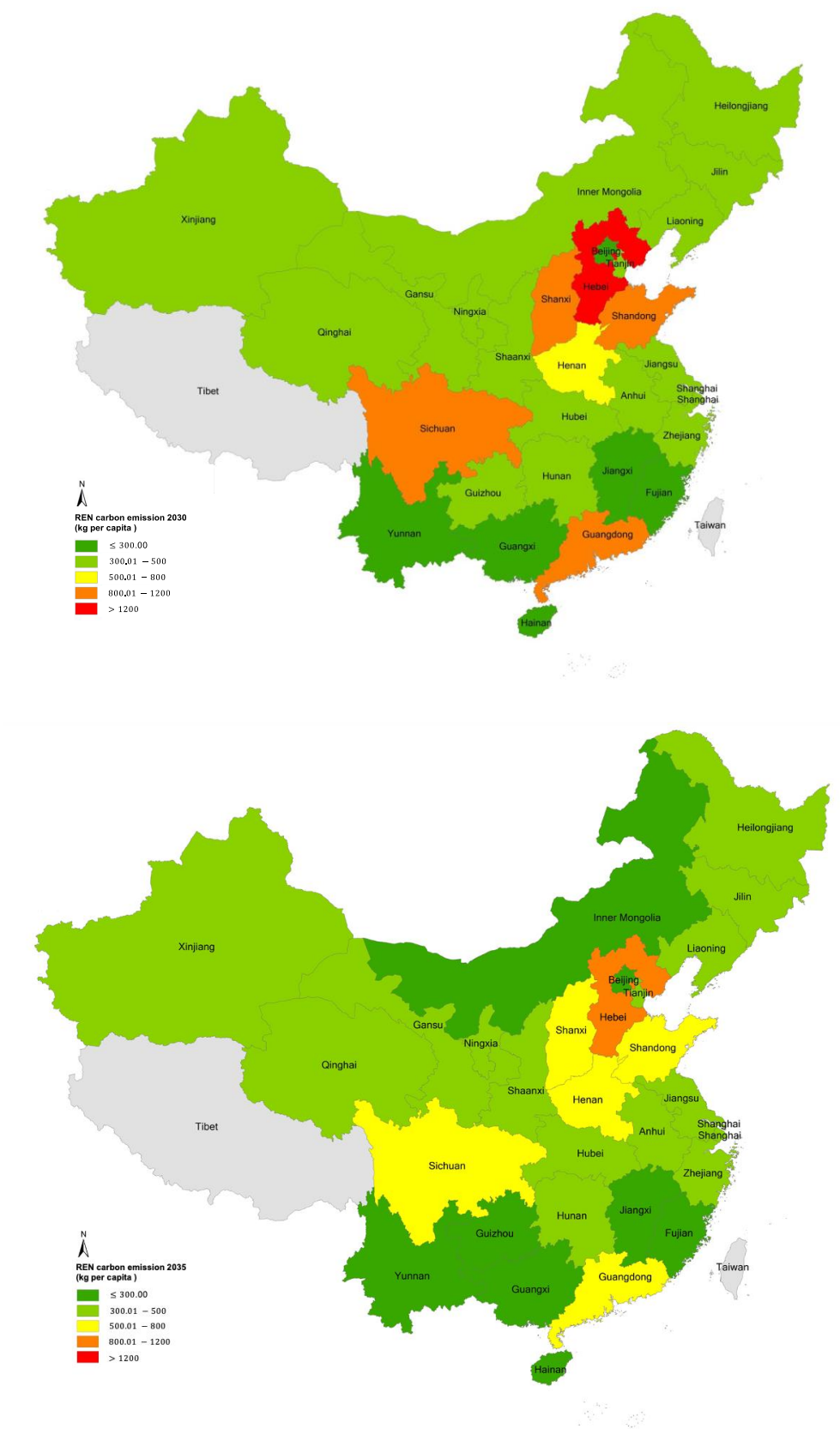
Fig. 40 Provincial carbon emission per capita by REN (2030&2035)

Renewable energy is the key to overcoming energy poverty, providing needed energy

services without harming human health or ecosystems, and transforming economies to

support development and industrialization. An increased rate of electrification facilitates the expansion of renewable energy utilization to a greater extent. Electricity is a driving force behind digital information technology and communication technology, and its role in sustaining economic development that is environmentally and socially responsible cannot be overstated. As China advances towards high penetration of renewable energy, electricity is expected to play a critical role in driving the energy consumption revolution in the transport, building, and industrial sectors. Consequently, to achieve high renewable energy penetration, prioritizing electricity development is imperative. This requires accelerating the transformation of the power system to prioritize resource sustainability, energy diversification, system flexibility, and consumer-oriented development. The share of residential sector electricity consumption in total electricity consumption is increasing year by year (Fig. 41).
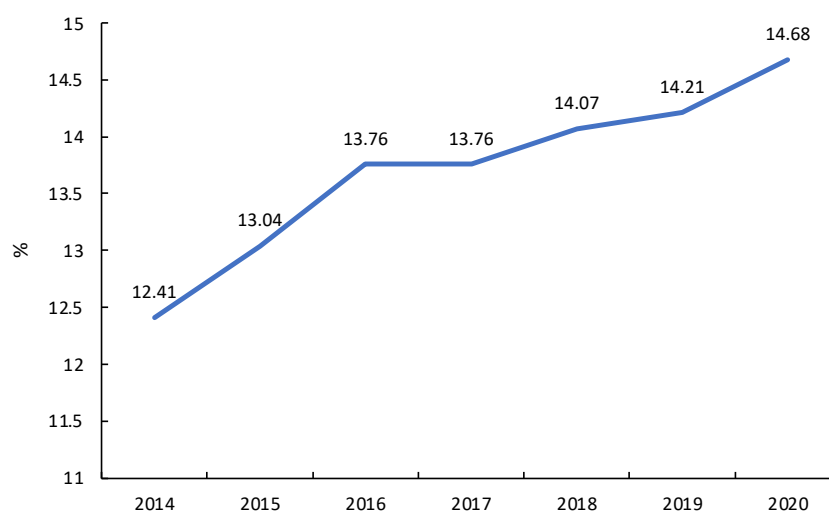
Fig. 41 Percentage of electricity consumption in the residential sector[9]

4.3.4 Comparison

In Fig. 42, a comprehensive analysis of the energy poverty index across three different scenarios is presented. The results indicate a downward trend in all scenarios, with the scores being relatively similar in both the BAU and CER scenarios. However, the most significant decrease in the energy poverty index is observed in the REN scenario. This suggests that the REN scenario outperforms the other scenarios in terms of addressing

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[9] Data source: China Statistical Yearbook

energy poverty and promoting sustainable energy practices.

Further examination of the three categories of energy poverty indices (Fig. 43) reveals valuable insights. The energy consumption and generation cleanliness index play a crucial role in improving energy poverty and exhibit the most substantial declining trend across all three scenarios. Over the period from 2021 to 2035, this index shows a remarkable decline of over 50%, highlighting the rapid development and widespread adoption of renewable energy applications. This significant decrease underscores the successful integration of clean energy sources and technologies, leading to a more sustainable energy landscape. The energy availability index demonstrates an approximate 40% decrease, indicating an improvement in household access to modern energy sources. This positive trend signifies progress in ensuring that households have reliable and adequate access to energy services, which is essential for enhancing their quality of life and enabling socio-economic development. On the other hand, the energy affordability and efficiency index shows a slower rate of decline compared to the historical year. However, it still contributes significantly to the overall EPI. The relatively slower decline in this index may be attributed to factors such as the slowdown of economic development, limited growth in disposable income, and more efficient utilization of electric appliances. Despite the slower decline, the index's higher contribution to the EPI indicates the importance of addressing energy affordability challenges and promoting energy efficiency practices to combat energy poverty effectively.

In summary, the REN scenario stands out as the most effective in reducing energy poverty, while the energy consumption and generation cleanliness index display the most substantial improvement. The energy availability index reflects enhanced access to modern energy sources, while the energy affordability and efficiency index, though declining at a slower rate, continues to contribute significantly to the overall EPI. These findings emphasize the need for sustainable energy practices, greater renewable energy adoption, and targeted measures to improve energy access and affordability, ultimately

leading to a more equitable and sustainable future.
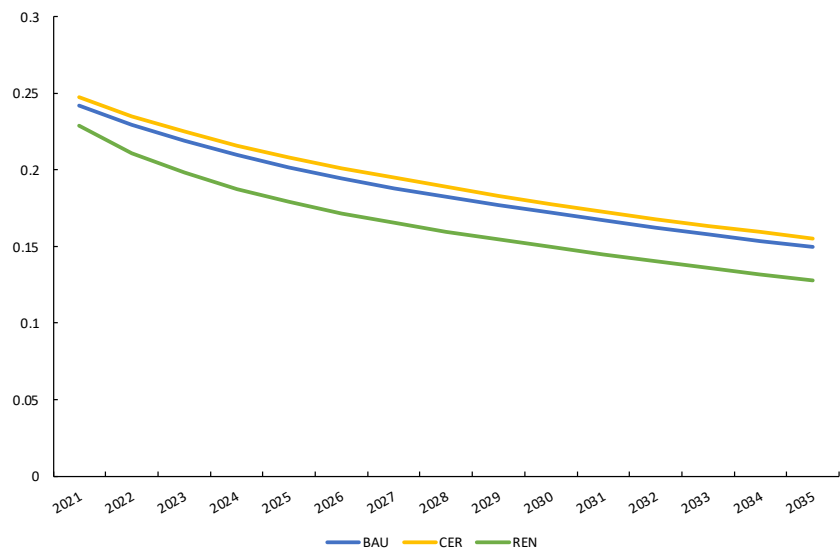
Fig. 42 Energy poverty index under three scenarios (2021-2035)
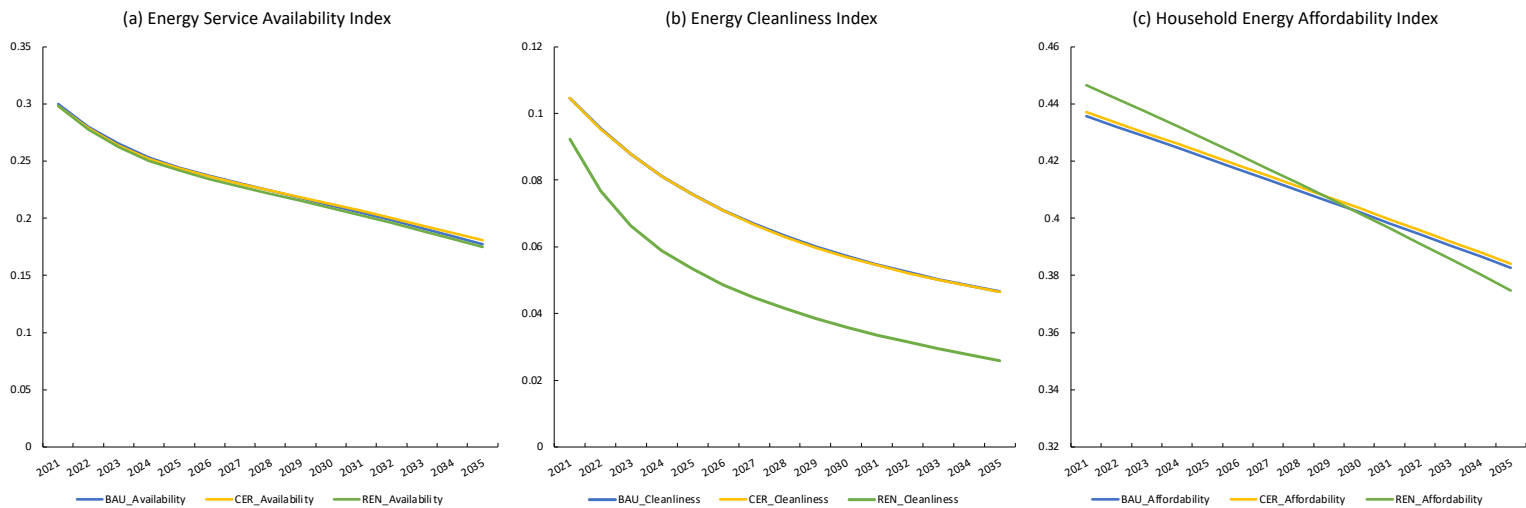
Fig. 43 Energy poverty sub-indices

Fig. 44 illustrates a graph that compares the total emissions across three different scenarios. The analysis reveals distinct trends: carbon emissions exhibit an upward trajectory in the BAU scenario, while both the CER and REN scenarios showcase a decline in emissions. Notably, the decrease in emissions is more pronounced in the REN scenario, indicating its superior efficacy in reducing overall carbon emissions and mitigating the impacts of climate change.

Examining the national average per capita emission (Fig. 45), a similar pattern emerges. As expected, the BAU scenario demonstrates an increase in per capita emissions,

suggesting an unsustainable path. Conversely, both the CER and REN scenarios exhibit a decline in per capita emissions, aligning with the objective of reducing individual carbon footprints and fostering sustainable practices on a national scale.

When considering these findings alongside the EPI and carbon emissions resulting from residential consumption, the REN scenario emerges as the optimal choice. The REN scenario not only leads to a significant reduction in carbon emissions but also contributes to addressing energy poverty by providing cleaner and more accessible energy sources. By prioritizing renewable energy solutions, the REN scenario offers a comprehensive approach that simultaneously tackles environmental and social challenges, thereby fostering a more sustainable and equitable future.

In brief, when considering the EPI and carbon emissions from residential consumption, it shows that the REN scenario presents the optimal choice. By promoting renewable energy and facilitating carbon emission reduction, this scenario effectively addresses sustainable development goals, mitigates climate change, and alleviates energy poverty.
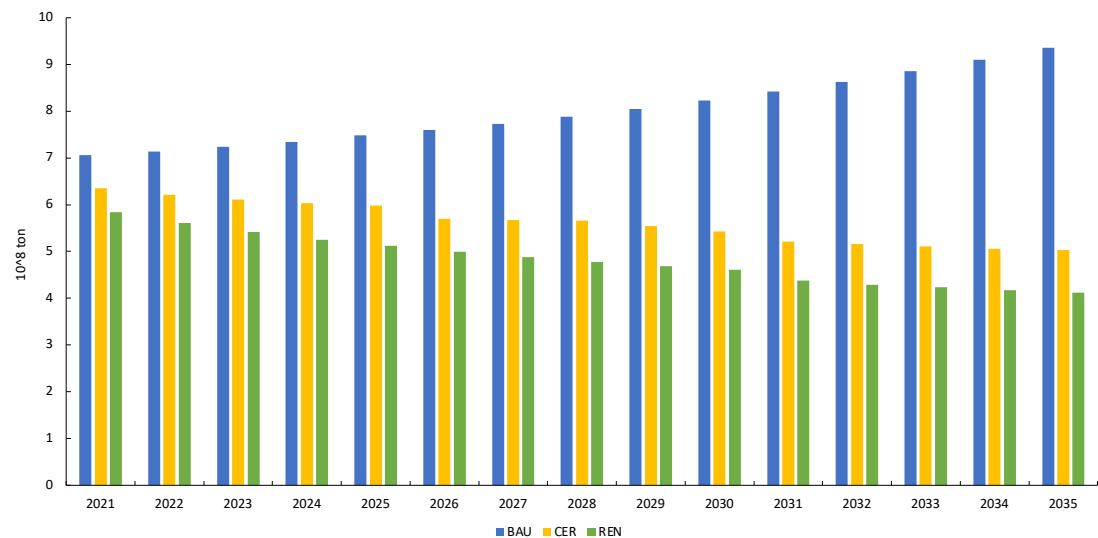
Fig. 44 Total emissions under three scenarios (2021-2035)
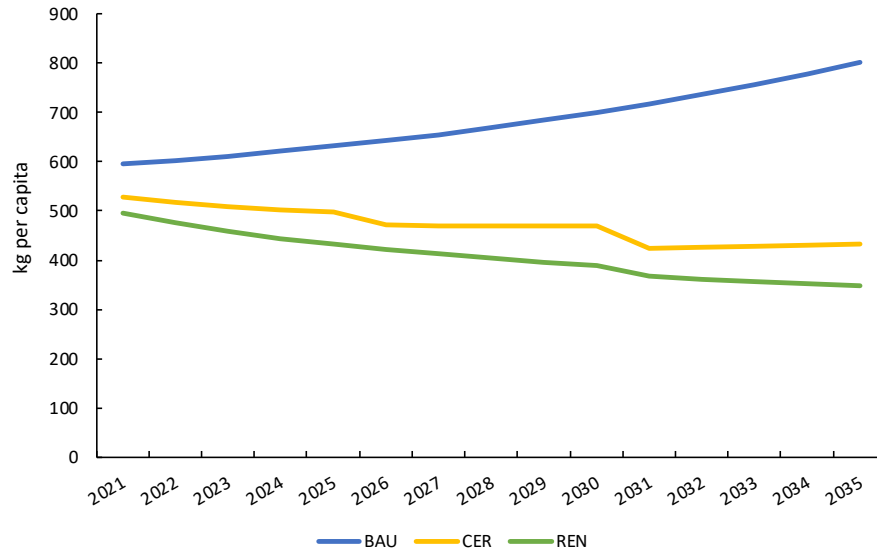
Fig. 45 Per capita emission under three scenarios

4.4 Conclusion

This chapter constructs a comprehensive measurement index system for energy poverty in China, applied at the provincial level, and makes urban-rural comparisons and regional comparisons. Carbon emissions from residential energy consumption are also measured, and a comparative analysis with the energy poverty index is done. Then energy poverty levels and carbon emissions are calculated for three different scenarios. The main conclusions are as follows:

First, the overall level of energy poverty in China exhibits a decelerating trend, albeit with a gradually diminishing rate of deceleration. The reduction in energy poverty primarily stems from advancements in energy affordability and cleanliness. Since the pricing mechanism of electricity and natural gas has not undergone substantial changes, residential energy consumption prices have not witnessed significant increments. Meanwhile, disposable income has experienced steady growth, accompanied by an increase in the utilization of household appliances. Consequently, the affordability of household energy consumption has significantly improved. Moreover, the rapid expansion of renewable energy power generation has augmented the availability of residential electricity and natural gas, and governmental administrative measures have

led to a decline in coal consumption, thereby contributing to enhanced energy cleanliness.

Second, there are significant differences in the level of energy poverty between urban and rural areas in China, and rural areas are relatively more threatened by energy deprivation. Moreover, there are also huge differences among provinces and cities, and the speed of energy poverty alleviation as well as the core issues of energy poverty are inconsistent. The northern area shows higher energy poverty index than the southern area of China; western regions are more energy-deprived compared with eastern regions. By comparing provincial EP sub-indices, energy service availability and affordability indicate the correlation between social-economic development and energy poverty, while energy generation and consumption cleanliness alleviates energy poverty in northern and southwestern provinces (e.g., Inner Mongolia, Sichuan, Yunnan) to some extent.

Besides, the spatial and temporal patterns of the energy poverty index and CO_2 emissions in China's provincial regions differ significantly from 2014 to 2020. By comparing the three different energy consumption scenarios, it is found that in the BAU scenario, the energy poverty index continues to decline, suggesting improvements in energy access and affordability. However, concurrently, carbon emissions increase year by year, aligning with the trends observed in historical data. This emphasizes the challenge of addressing energy poverty while simultaneously tackling the escalating issue of carbon emissions under the BAU scenario.

In contrast, the carbon reduction scenario showcases promising outcomes. Both the energy poverty index and residential carbon emissions demonstrate a decreasing trend, indicating that concerted efforts towards carbon reduction can lead to improvements in energy poverty alleviation. The decline observed in both indices signifies the positive impact of implementing measures to mitigate carbon emissions and promote sustainable energy practices.

Among the three scenarios, the renewable energy scenario stands out as the most effective in simultaneously reducing the energy poverty index and residential carbon emissions. The significant decreases observed in both indices underline the transformative power of renewable energy adoption. This scenario exemplifies the potential of clean and sustainable energy solutions in addressing energy poverty while contributing to the overarching goal of mitigating carbon emissions.

Chapter 5 Further Discussion and Conclusion

5.1 Further Discussion

5.1.1 Employment

The energy ladder theory argues that the household increases the use of clean/modern energy with the increment of income (Davis 1998; Hosier and Dowd 1987), thus reducing the household energy poverty level. Given that employment precarity is associated with job insecurity and instability, it is likely to lead to income inadequacy or low labor income. Accordingly, it could be expected that low labor income is a channel through which employment precarity will influence energy poverty (Koomson and Awaworyi Churchill 2022).

The transition towards a green economy and a decarbonized energy system has far-reaching socio-economic implications globally and in China. The first to be affected are high-energy-consuming and high-polluting industries, like coal and steel industries. The severe pressure on the employment of the coal industry is the result of the combined impact of several factors. On the one hand, the pressure to cope with climate change has pushed more and more clean energy to replace the use of coal, reducing the demand for coal; on the other hand, China's attention to ecological and environmental protection has been increasing in recent years, in order to control air pollution and reduce environmental pollution caused by the use of coal, it has also pushed some regions to put forward increasingly strict environmental requirements for the use of coal, and such coal control measures have also This coal control measure has also suppressed the demand for coal in some areas. In addition, the overcapacity in the coal industry is also relatively serious and is one of the sectors most directly and significantly affected by the implementation and enforcement of the "de-overcapacity" policy. In the context of supply-side reform, the task of eliminating backward production capacity in the coal sector also means that the entire industry will have many employees will be affected by this. The natural increase in labor productivity will also contribute to the tremendous

pressure currently faced. These factors combine to result in some coal resource-based cities and regions facing more concentrated and urgent pressure to reduce employment in the short term. The number of employees in the mining industry has been decreasing year by year since 2013 (Fig. 46). Local governments and enterprises have adopted a number of policies, including job placement, social security, industrial replacement, and regional development. In the context of energy transition, a just transformation of society will not be accomplished spontaneously but must rely on sound planning and policy guidance. It is important to recognize that those coal resource cities, groups of workers and regions that have long depended on coal for their livelihoods are unlikely to find alternative sources of income and new pillar industries overnight. Therefore, this transformation is not simply about decommissioning and exiting polluting sectors and enterprises, but also about creating new jobs, new industries, new skills, new investments, and new opportunities to create a more equitable and dynamic economy.
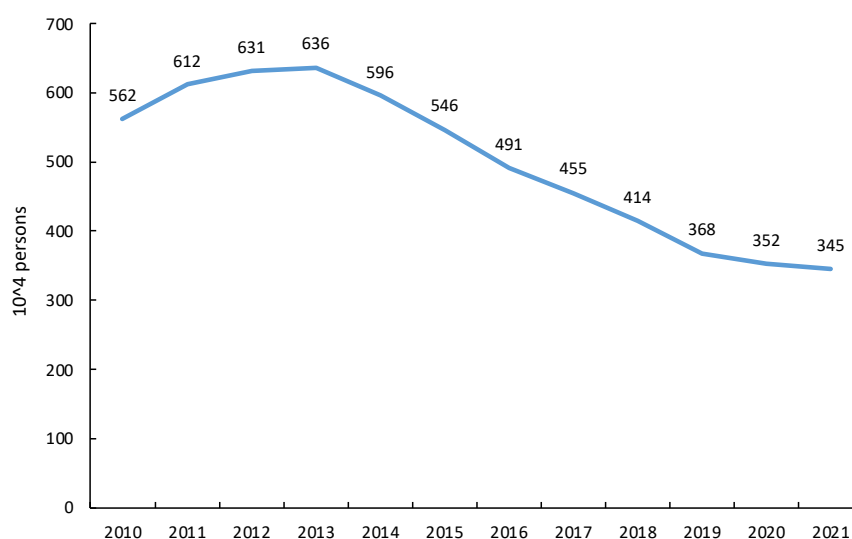
Fig. 46 Number of employed persons in the Mining Sector of China (urban enterprises) (2010-2021)

Decarbonization will cause related job losses, but at the same time, the transition to clean energy could lead to more new jobs than even the jobs lost in the declining fossil fuel industry. Energy development and construction have created a large number of employment opportunities for poverty-stricken areas and played an important role in poverty alleviation. According to the report from IRENA & ILO (2022), A growing number of countries are creating jobs in renewable energy, with almost two-thirds of

the jobs in Asia, and China alone accounting for 42% of the global total. China is a major manufacturer and installer of solar photovoltaic panels and is creating more and more jobs for offshore wind power, including activities of manufacturing, construction and installation, operation and maintenance. In addition, the new energy vehicle industry is growing vigorously, and the entire chain from manufacturing, sales, and construction of supporting facilities is also creating many new jobs. Data shows that China's renewable energy sector provided employment to 5.4 million individuals in 2021, indicating an increase from the 4.7 million employed in 2020. Studies also show that nonfarm employment in rural areas can have a noteworthy effect on the income of its residents, while also contributing positively to energy efficiency and effective energy consumption per capita (Ma et al. 2023). Off-farm incomes are more stable (Finger and Schmid 2007), and the non-agricultural job has a significant negative impact on household energy poverty in China (Lin and Zhao 2021).

Economic transformation will not only cause changes in the overall level and structure of employment but may also affect the quality of employment. Greener products and services often require higher skill levels. Companies and departments require higher environmental performance and environmental protection capabilities, which may also require enterprises to provide more stable formal employment and build more formal enterprises. Green growth sectors and occupations may provide more or less equal employment opportunities to women, men or job-seeking groups. Likewise, these jobs may provide workers with opportunities to exercise their rights to organize and bargain collectively (ILO 2013). In addition to having an impact on employment, the transition to a green economy will also affect income levels and distribution, as well as poverty reduction. Improved eco-efficiency and access to new growth markets can lead to higher profits, revenues and wages, which requires governments to implement macroeconomic policies and environmental policies, coupled with investments in skilled labor and business development opportunities, to provide a strong impetus for sustainable development.
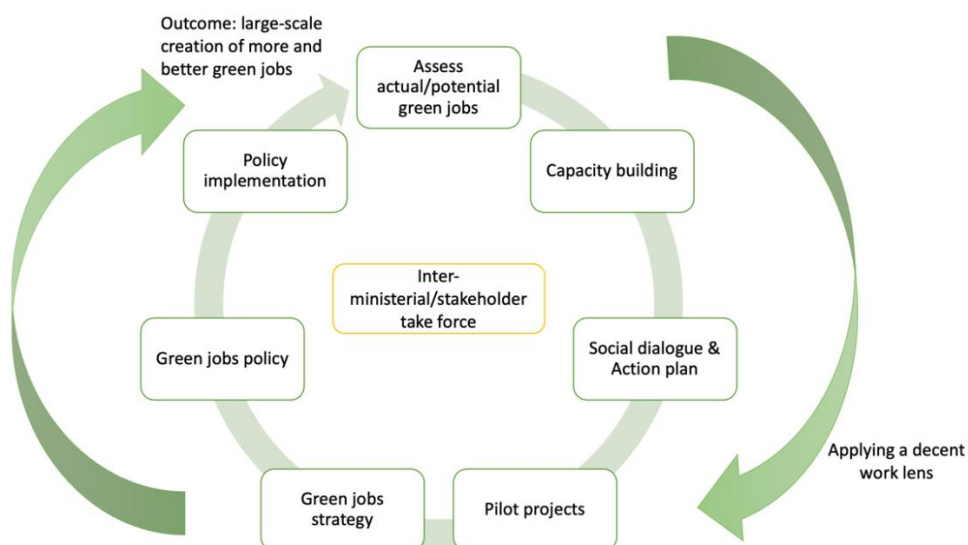
Fig. 47 The green jobs program cycle[10]

5.1.2 Economic aspects

5.1.2.1 Cost for the energy transition

A green and low-carbon transition in the energy sector is critical to achieving global climate goals, and a stable, high-quality and low-cost renewable energy (e.g., PV, wind) supply chain will fundamentally drive the green transition in the energy sector, providing a solid foundation for achieving the goals of energy poverty eradication and carbon neutrality. It requires a substantial increase of capital-intensive clean energy assets, which have relatively high upfront investment costs and lower operating and fuel expenditures over time.

One of the opportunities is the falling cost of renewable energy generation. The Levelized Cost of Energy (LCOE) of solar PV has decreased by 89% from 2010-2021 (Fig. 48), and 66% for onshore wind power (Fig. 49)[11]. The development and cost reduction of renewable energy underpins the energy transition in China. According to Bloomberg NEF (BNEF, 2023), global solar investment jumped to $308 billion in 2022,

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and investment in the second-largest sector, wind, stayed roughly stable at $175 billion. China accounted for a substantial 55% share of global renewable energy investment, as it committed an impressive $164 billion towards the establishment of new solar farms and an additional $109 billion towards the development of new wind farms. While the investment figures are the highest ever, yet there is still a huge gap in renewable energy investment to be on track for the 2050 global net-zero emission goal. At present, China's photovoltaic industry has formed the world's most complete industrial supporting environment and supply chain system, and the output of each production link exceeds 80% of the global market share. However, clean energy investment from private sector is still required.
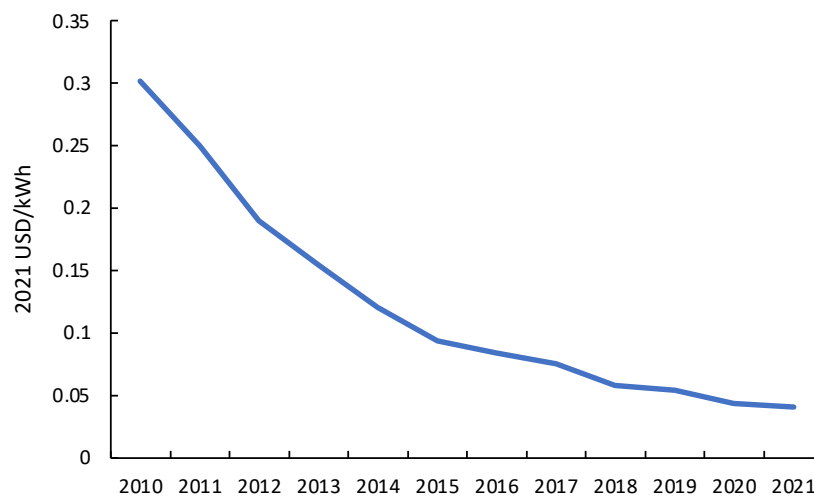
Fig. 48 Weighted-average LCOE of newly commissioned utility-scale solar PV projects in China
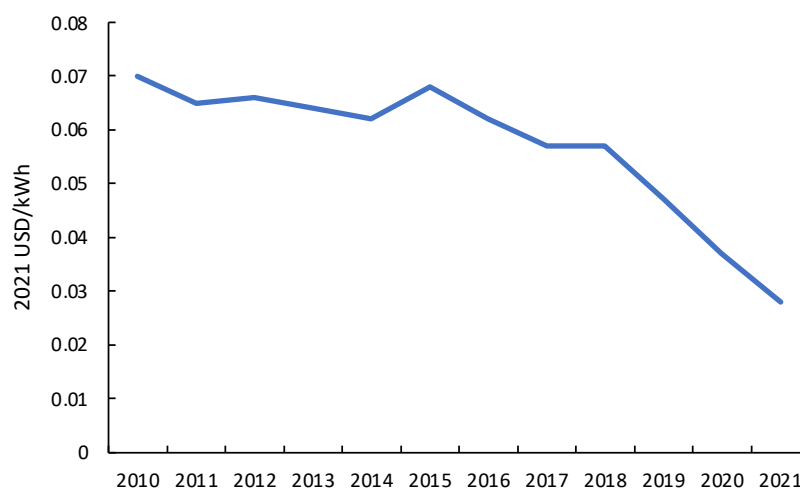
Fig. 49 Weighted-average LCOE of newly commissioned onshore wind projects in China
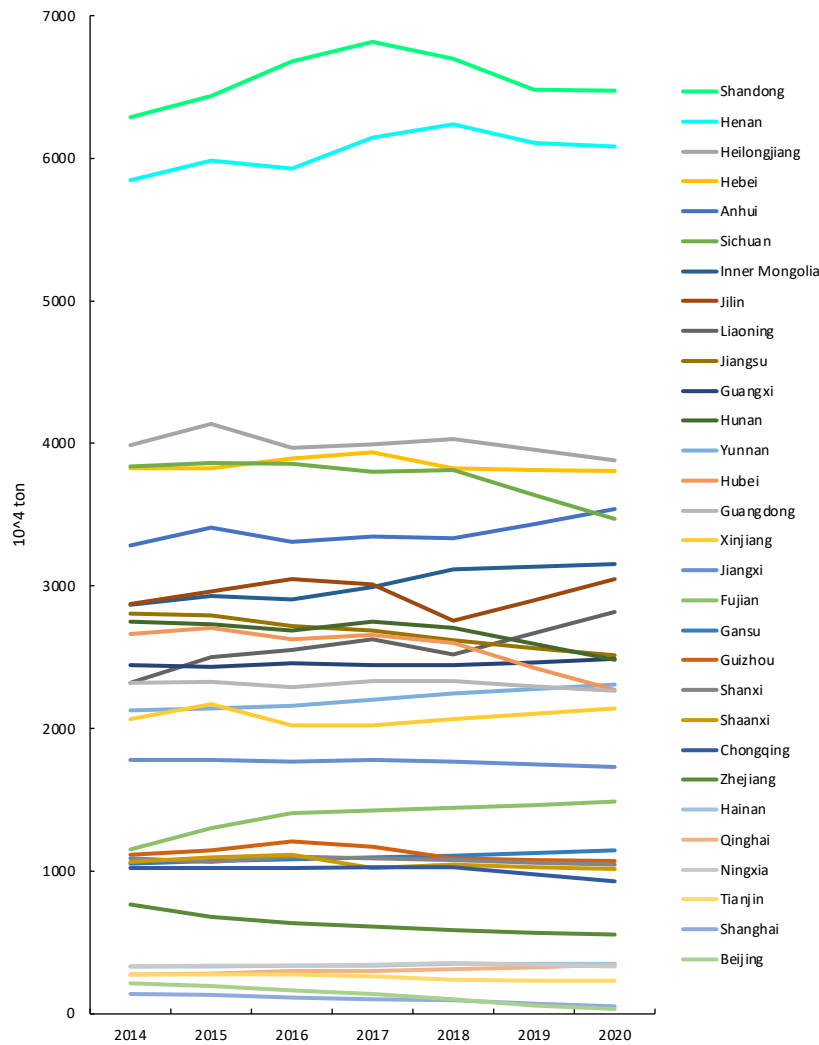
Fig. 50 Biomass energy estimation (2014-2020)[12]

Besides, studies have suggested that the full utilization of biomass resources suitable for power generation can generate the maximum negative emissions of 1.6 Gt CO_2 (Zhang and Chen 2022). China's biomass energy is rich and has great potential for development. There are many kinds of biomass resources in China, mainly including agricultural waste and waste from the processing industry of agricultural and forestry products, fuelwood, human and animal manure, household waste, etc., different provinces have different resource endowments (Fig. 50). The National Development and Reform Commission (NDRC) set a goal in 2019: to produce 30 billion cubic meters of biomethane by 2030, mainly to replace coal consumption in rural areas.

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[12] Data source: Author's calculation based on straw, animal manure, forest and garbage resources in each province.

Studies show that government subsidies are the main force supporting the medium-, small-, and micro-sized renewable energy enterprises (Yang et al. 2019).

5.1.2.2 Electricity market reform

With the economic restructuring, the growth in demand for electricity is shifting towards the tertiary industry and residential areas. There is a large potential for per capita electricity consumption to increase, and the substitution of electricity and the improvement of electrification rates will continue to drive up demand for electricity. The transition to a low-carbon electricity system is a key component of energy poverty reduction and climate change mitigation. The trilemma facing the energy sector involves the challenge of simultaneously ensuring the security of energy supply, promoting sustainability, and maintaining affordability. This means that achieving sustainability, or green growth, may not always be the most cost-effective option for consumers. Therefore, interventions in the market are likely to be necessary to achieve the green objectives in the electricity supply industry.

At present, in parallel with the transformation of power generation structure and infrastructure, China is also carrying out extensive reforms in the power sector to strengthen the role of market-oriented mechanisms in determining the operation of the power sector and improving system efficiency. Electricity dispatch and prices in China are mainly determined by administrative means. Since the implementation of the power system reform in 2002, the power industry has broken away from the system constraints of exclusive power supply, and initially formed a diversified competition pattern for power market players. In 2015, the State Council launched a new round of major power system reforms aimed at strengthening the role of the market in power pricing. Since 2019, China has gradually liberalized the price of coal-fired electricity, canceled the previously unified benchmark on-grid electricity price for coal-fired power generation, and allowed the price of coal electricity to fluctuate within 20% of the benchmark price (NDRC 2019). In October 2021, China will adopt further important reforms in

electricity market pricing, allowing coal electricity prices to fluctuate within 20% of the benchmark price, and the electricity prices of high energy-consuming enterprises and electricity spot transactions are not subject to this restriction (NDRC 2022). In response to the current situation that the electricity market system is divided into regional and provincial electricity markets, China plans to accelerate the construction of a national unified electricity market system by 2025 to improve the efficiency of resource allocation and better support the development of renewable energy consumption by increasing cross-provincial electricity trading, improving the stability of the power system and flexible regulation capacity.

5.1.2.3 Pricing Policy

Energy price is another level through which energy poverty and carbon emission have been traditionally addressed. Many countries and jurisdictions have attempted to address these two problems and spur development through subsidized energy prices or social tax/tariff policies, which are, however, a double-edged sword.

Subsidized energy prices need to be very carefully used in addressing energy poverty. While subsidized energy prices or social tariffs can serve as a temporary solution to address energy poverty, particularly during the transition to a low-carbon residential sector, their effectiveness in solving the problem can be hindered if implemented without accompanying energy efficiency measures. In fact, these policies may have counterproductive effects, potentially trapping vulnerable households in energy poverty by removing incentives for household-level energy efficiency investments. The absence of proper economic signals due to artificially low energy prices can result in a capital stock characterized by lower efficiency than what is economically rational. Consequently, when subsidies are eventually phased out, the inefficient equipment and infrastructure lead to significantly higher energy costs over the lifecycle compared to if they were optimized at the time of investment. This situation forces households into unnecessarily high energy expenditures, particularly in the case of long-lasting energy-

consuming equipment and infrastructure, such as houses or apartments. These effects can persist for decades, creating a long-term burden for affected households. For example, the Chinese government selected over 40 pilot cities in the Beijing-Tianjin-Hebei region and Fenhe-Weihe plain for clean winter heating renovation project, with a total of 112.8 billion CNY invested in subsidies from 2017 to 2019 (NDRC 2020). The subsidies last three years and would be phased out gradually. A household survey has shown that subsidies phasing out or cancellation would significantly increase the heating burden of rural residents and bring "coal reverse substitution"(Chen et al. 2022). Therefore, the subsidy policy needs further optimization.

On the other side, price signal is a key policy tool to reduce carbon emissions, but strong climate change action would worsen energy poverty. Carbon prices, when effectively managed, serve as a potent tool for demand-side climate policies as they form an integral part of energy prices (Dellink et al. 2010). As we move towards a carbon-constrained economy, it is anticipated that carbon prices will rise in real terms, potentially leading to increased energy poverty level. This scenario could give rise to a trade-off between climate change mitigation and alleviating energy poverty, creating a potential conflict between the welfare of present and future generations. To address this, it is crucial to tackle energy poverty through alternative means, preferably through energy efficiency measures, to mitigate the potential conflict and achieve both goals effectively. Back in the 1990s, Boardman (1991) has raised concerns about the potential adverse effects of implementing a carbon tax in the UK on the well-being of energy-poor households. It was highlighted that environmental policies could exacerbate the deprivation faced by socioeconomically disadvantaged families. To address this issue, a possible solution lies in ensuring high levels of insulation in the homes of energy-poor households. Additionally, it is crucial to prioritize the installation of low- or zero-carbon measures, such as solar thermal or PV systems, in these homes. When combined with a feed-in tariff, these measures can even generate income for these families (Boardman 2009). Other experts have emphasized the need for careful implementation, if at all, of carbon taxes in the residential sector to prevent them from disproportionately

impacting the energy-poor population. The price-based measures like carbon taxes risk being regressive when not accompanied by complementary measures, and could trigger concerns around fairness, as vulnerable citizens usually spend a higher share of their income on carbon-intensive goods to meet their basic needs (Vandyck et al. 2023). It is argued that carbon taxes should specifically target high-income households to avoid regressive effects (Healy 2003), and low-income targeted revenue recycling can bring progressive outcomes while mitigating energy poverty (Vandyck et al. 2023).

5.1.3 Energy Efficiency

Maintaining global growth and supporting development in emerging economies implies a sharp rise in consumption habits. Meeting this need requires a transformation of the existing energy system. Energy efficiency is the "first fuel": reining in the scale of this unprecedented challenge, supporting net zero energy goals at lower costs, and delivering a wide array of benefits for society. When it comes to energy efficiency in the residential sector, it is mainly about building energy efficiency and energy-consuming appliances.

Building retrofits and energy-efficient products are effective to reduce energy consumption in a home and can result in significant cost savings over time. Efficient building and product design and technologies can minimize energy waste and provide more sustainable and cost-effective energy options, thus contributing to improving living conditions in energy-poor areas. building energy efficiency plays a significant role in reducing carbon dioxide emissions. The construction sector is one of the major sources of global greenhouse gas emissions, with a significant portion attributed to building energy use. By implementing energy-efficient building design and technologies, energy consumption in buildings can be reduced, leading to a decreased reliance on fossil fuels and a subsequent reduction in carbon dioxide emissions. To scale up building efficiency renovations, governments can create net zero or positive energy building codes supported by minimum energy performance standards at the point of

sale or lease, as well as building performance ratings and disclosure programs, with careful design and implementation. Performance standards could also be implemented on energy-intensive appliances, such as air conditioning, lighting, and industrial motors. Currently, more than 80 countries employ some form of minimum energy performance standards, but those standards are too low to drive improvements, as they remain below the technological potential that exists.

One potential conflict is the rebound effect, which is undesirable due to the energy efficiency improvement in end-use sectors. In energy-poor households, efficiency gains may be experienced more as improvements in comfort, such as higher indoor temperatures or a larger heated area, rather than as reduced energy consumption (Ürge-Vorsatz and Tirado Herrero 2012).

5.2 Conclusion

Energy poverty and climate change are significant global challenges with far-reaching implications. Energy poverty hinders the sustainable development of countries, particularly in the case of developing nations. It impacts various aspects of economic growth, education, healthcare, social equity, and contributes to social and environmental pressures. On the other hand, climate change poses a major threat to the sustainable development of human society. Addressing these issues requires integrating energy issues into poverty eradication policies to ensure lasting results and mitigate the adverse effects of climate change on impoverished populations.

To shed light on the extent of energy poverty in China, this study employs a comprehensive index system consisting of 19 indicators to assess energy poverty across 30 provinces. The analysis also explores the carbon emissions resulting from residents' energy consumption. The results in this study reveal an overall decline in energy poverty levels in recent years, although rural areas continue to face higher energy deprivation compared to urban regions. Moreover, significant disparities are observed

among provinces (municipalities), not only in the pace of energy poverty alleviation but also in the factors driving energy poverty. Besides, the energy poverty index exhibits a negative correlation with residents' carbon emissions levels.

The study then establishes three different scenarios: BAU (Business-as-Usual), CER (Carbon Emission Reduction), and REN (Renewable Energy) scenarios to assess changes in the energy poverty index and carbon emissions. Through a comparative analysis of these scenarios, it becomes evident that under the BAU scenario, the energy poverty index continues to decline, but carbon emissions show an annual increase, consistent with historical data. In contrast, the CER scenario leads to a decrease in both the energy poverty index and residential carbon emissions. The most substantial reductions in both indicators are observed in the REN scenario, underscoring the importance of renewable energy development for addressing energy poverty and reducing carbon emissions.

Furthermore, this research discusses the relationships between energy poverty, energy transition, and employment. It examines how the costs of transitioning to renewable energy sources, the marketization of electricity markets, and pricing policies influence the overall progress of the energy transition. Additionally, it highlights the crucial importance of energy efficiency in this context.

5.3　Policy Recommendations

5.3.1　Expanding rural energy solutions and fostering clean energy support

The results discussed above indicate that the modern energy usage in rural areas is still insufficient and energy price is one of the factors that hinder rural residents from using it, which highlights the critical need for China to maintain its focus on ensuring adequate and affordable access to clean energy and encourage the diversified development of rural energy supply methods. Biomass energy, given the abundant resources of straw, livestock breeding, and domestic waste in China, holds significant

development potential. Promoting the use of biomass, along with other renewable energy sources such as hydro, wind, and photovoltaic power generation, based on local natural conditions and endowments, will contribute to a more diverse and sustainable energy mix. It is also crucial to provide training and capacity-building programs. Technical training should be offered to local communities, entrepreneurs, and technicians to equip them with the necessary skills to install, operate, and maintain clean energy systems. Empowering rural communities with the knowledge and expertise to adopt and manage clean energy solutions promotes self-sufficiency and sustainability, enabling them to harness the benefits of clean energy in a long-term and independent manner.

The development of renewable energy is key to reducing both energy poverty and carbon emissions, which means it is imperative to increase support for clean energy initiatives. Governments at various levels should continue to establish favorable policies and regulatory frameworks that prioritize clean energy sources. One essential step is to set and achieve renewable energy targets, providing a clear roadmap for clean energy development. Governments can offer financial incentives and subsidies to attract investments in clean energy projects, making them more economically viable. Streamlining permitting processes and ensuring grid access for clean energy projects will further facilitate their implementation and integration into the energy system.

Increasing investment in research and development (R&D) is crucial for advancing clean energy technologies. Collaboration between governments, research institutions, and private sector entities can drive innovation, improve the efficiency of clean energy solutions, and make them more affordable. R&D efforts can focus on developing scalable renewable energy technologies suitable for rural areas, including decentralized solar systems, bioenergy solutions, and small-scale wind turbines. In the future, it is essential to optimize the generation of renewable energy and traditional energy sources within the network portfolio. By promoting a balanced approach, China can simultaneously enhance the overall level and quality of power supply. This optimization

can involve smart grid technologies, energy storage solutions, and the integration of renewable energy sources with existing infrastructure.

Besides, the Energy Poverty Index can also be used as a reference for government performance evaluation, thus encouraging governments to take measures to scale up rural energy solutions and strengthen clean energy support.

5.3.2 Improving energy efficiency and enhancing synergies between renewable energy and energy efficiency measures

Improving energy efficiency reduces energy consumption and energy costs, and thus more sustainable. Governments play a crucial role in promoting the scaling up of building efficiency renovations to achieve energy savings and sustainability goals. One effective approach is the establishment of building codes that aim for net-zero or positive energy, encouraging the construction of highly energy-efficient buildings. These codes can incorporate minimum energy performance standards during sales or leases, ensuring that buildings meet specific energy efficiency criteria. Furthermore, the implementation of building performance ratings and disclosure programs can enhance the effectiveness of energy efficiency measures. By assessing and publicizing the energy performance of buildings, potential buyers or tenants can make informed decisions based on the energy efficiency of the property. This transparency drives demand for energy-efficient buildings and encourages building owners to invest in energy-saving measures.

To address energy-intensive appliances such as air conditioning, lighting, and industrial motors, governments can enforce performance standards. These standards set minimum efficiency requirements for these appliances, promoting the use of energy-efficient technologies and reducing energy consumption.

The integration of next-generation digital technologies can significantly enhance

residential building efficiency and encourage behavior changes that promote energy savings. Technologies such as smart meters and thermostats, in-home displays, mobile applications, and web-based portals provide real-time feedback on energy consumption patterns to consumers. This information empowers individuals to make informed decisions about their energy usage, leading to more efficient practices and behavior changes that reduce energy waste.

Moreover, research indicates that internet development can contribute to alleviating energy poverty levels by promoting economic development and technical progress (S.H. Zhang et al., 2023). To leverage this potential, governments should implement an "Internet + Energy" policy. This policy involves promoting the construction of a modern energy system while strengthening the integration of the energy sector with the internet. It requires focusing on establishing the necessary energy internet infrastructure and information and communication infrastructure to facilitate coordination with the energy supply side. Simultaneously, efforts should be made to construct intelligent energy consumption systems and intelligent energy operation platforms on the demand side, enabling efficient energy management and optimization.

Renewable energy and energy efficiency are mutually positive in terms of technology and policy. Renewable energy can play a larger role in primary energy supply if energy service delivery is more efficient. As the proportion of renewable energy increases, a corresponding reduction in primary energy is required to provide the same level of energy service, thereby minimizing the environmental and economic costs of the overall system. The deployment of distributed renewable energy combined with energy efficiency improvements can reduce peak electricity demand while minimizing transmission losses and relieving transmission bottlenecks. In addition, renewable energy targets and policies have the potential to galvanize more investment in energy efficiency improvement projects. The more ambitious the renewable energy development goals, the more indispensable the focus on energy efficiency. If energy efficiency upgrading measures are implemented, the cost of achieving long-term

renewable energy development goals is lower. If a country implements renewable energy and energy efficiency measures in parallel, the overall cost of achieving these goals will decrease.

By implementing these strategies, governments can foster the widespread adoption of energy-efficient practices in buildings, encourage behavior changes, and leverage digital technologies to drive energy savings and sustainability. These initiatives contribute to the overall goals of reducing energy consumption, mitigating climate change, improving energy affordability, and promoting a more intelligent and sustainable energy future.

5.3.3　Focusing more on employment during the transition

As discussed previously, employment is deeply affected during the transition towards a green economy and a decarbonized energy system. Explore the implementation of economic diversification. The development of a clean energy industry brings substantial economic development opportunities and job creation. Integrate skills development policies with the vocational skills education and training system by revising and developing skills development policies but ensuring support for appropriate training, capacity building and curriculum development to transition to an environmentally friendly direction, using bilateral or trilateral mechanisms in promoting skills development.

Through skills needs assessment, labor market information analysis, and key skills development, we work with industry and training institutions to match skills supply and demand, anticipate and identify changing skills needs, and review, adjust and train programs for vocational skills profiles, give policy priority to relevant fields, and when allocating resources, give preference to key fields to encourage relevant science, technology, engineering, mathematics professional or general knowledge to be included in relevant curriculum or lifelong learning process.

Establish appropriate and collaborative labor market mechanisms and training systems that coordinate the needs of all stakeholders and ensure that education and skills policies are implemented at all stages. Promote equal access to skills training and recognition for all, especially for young people, women and workers in need of resettlement, including targeted skills training services for micro, small and medium-sized enterprises (MSME) employers and workers across borders, ensuring appropriate timing and duration, and providing supportive policies to enable everyone to find a balance between work, family, and lifelong learning.

Promote the provision of job-related skills training and time experience to help empower job seekers; develop a comprehensive skills development policy to upgrade skills for green jobs and align them with environmental policies, using a variety of appropriate tools such as skills certification; promote peer learning between businesses and workers, and provide education and training in green businesses to disseminate experience in sustainable practices and the use of green technologies. Assist enterprises, especially MSMEs, including cooperatives, to participate in skills training provided by government and training institutions, skills upgrading, anticipating future occupational profiles, occupational mobility, and employability skills that can be applied, etc.

5.3.4　Promoting financial and pricing policy innovation

Promote renewable energy and financial policy innovation. Lowering the price of high-quality energy affects household energy choices, thus promoting low-carbon development while alleviating energy poverty. For example, continue to promote policies such as photovoltaic poverty alleviation, and strengthen the operation and maintenance management of the completed photovoltaic power plants. Project development enterprises could provide employment for villagers and help households out of poverty to increase their income. Or encourage energy enterprises to play the advantages of capital and technology to build "PV+" modern agriculture. The local

government provides policy support and expands the marketing of products, while farmers increase their income through land leasing, participation in power plant operation and maintenance, farm labor, etc. In the future, it is important to further refine the subsidy incentives for different regions for different income groups and provide more innovative and diversified green financial products. Rapidly increasing investment in clean technologies also depends on enhancing access to low-cost financing, particularly in emerging and developing economies. While clean energy transitions rely on much higher levels of both equity and debt, capital structures also hinge on the widespread mobilization of low-cost debt, e.g., for new capital-intensive, utility-scale solar projects supported by long-term power purchase agreements.

Optimize subsidy policies. Taking into full consideration the unbalanced economic and social development of cities and the difference in the cost of clean energy paths, it is recommended that the central government financial subsidies be changed from subsidies according to administrative levels to fixed output subsidies graded according to economic levels and tilted toward poor areas. At the same time, a performance subsidy mechanism should be established to motivate local governments to establish long-term mechanisms, and additional incentive funds should be given to cities with "excellent" annual performance evaluation results. In the case of clean heating in northern China, as the beneficiaries, the heating cost of the original heating method should be borne by the residents, and the additional cost should be borne by the government, enterprises and residents. For the residents who have implemented coal-to-electricity and coal-to-gas conversion, the financial subsidies should be part of the cost, and the power grid or gas company should be part of the cost, and the proportion should be determined by city and technology after detailed economic research. Considering the large differences in residential income, we could consider taking reference from the U.S. low-income family energy assistance program, which distinguishes residents according to their economic income levels and sets differentiated subsidy standards, while giving the highest subsidy standards directly to key targets such as rural scattered-dependent special hardship cases, low-income

households, poor families with disabilities and poor households with cards.

Implement more tailored interventions on carbon pricing-based instruments. It is crucial to take carbon pricing policies combined with targeted compensatory measures to protect vulnerable populations and stimulate economic growth. For example, returning some of the carbon pricing revenues to the citizens, especially rural poor households, by an equal-per-capita dividend, tax reductions or investments in public infrastructure.

5.4 Limitations and Future Research

This research has certain limitations due to time constraints and individual capacity. Firstly, regarding the database, the study focuses on provincial-level data, overlooking intra-provincial differences and imbalances. Additionally, the research does not consider potential transitional changes in energy consumption and the structure of energy use resulting from technological advancements. The data used in this study primarily rely on statistical sources, and no household-level microdata, such as data obtained through questionnaires, are incorporated. Consequently, the assessment of domestic energy use affordability lacks comprehensive research on household energy consumption behavior.

Secondly, the analysis does not account for indirect emissions stemming from non-energy residential consumption goods and services. Moreover, due to significant variations in subsidies among provinces and municipalities, this study does not undertake a quantitative analysis of subsidies and equipment costs. Furthermore, the assessment of residential building energy efficiency, which is a vital indicator of energy-saving potential, is not included in this research.

For future studies, it is essential to expand beyond solely relying on statistical data and instead strive to obtain microdata at the household level. This would enable researchers

to delve into variables that consider factors related to technological progress, leading to more specific and detailed policy recommendations based on research findings. By incorporating household-level data and exploring a broader range of variables, researchers can gain a deeper understanding of energy consumption patterns, behaviors, and preferences, allowing for more precise policy interventions and targeted initiatives.

Appendix

Appendix A: Table of Emission factors by different sources

	Fuel Type	IPCC	NDRC	UN-China	Liu et al., 2015[13]
Net caloric value ($PJ/10^4$ *tonnes*, $10^8 m^3$)	Raw Coal	0.28	0.21	0.21	0.21
	Cleaned Coal	0.27	0.23	0.21	0.26
	Other Washed Coal	0.27	0.23	0.21	0.15
	Briquettes	0.26	0.17	0.21	0.18
	Coke	0.28	0.28	0.26	0.28
	Coke Oven Gas	1.88	1.74	1.88	1.61
	Other Gas	1.88	1.58	1.88	0.83
	Other Coking Products	0.43	0.28	0.43	0.28
	Crude Oil	0.42	0.43	0.42	0.43
	Gasoline	0.44	0.45	0.45	0.44
	Kerosene	0.44	0.45	0.43	0.44
	Diesel Oil	0.43	0.43	0.42	0.43
	Fuel Oil	0.4	0.4	0.4	0.43
	LPG	0.47	0.47	0.46	0.51
	Refinery Gas	0.5	0.46	0.42	0.47
	Other Petroleum Products	0.4	0.45	0.42	0.43
	Natural Gas	3.44	3.89	3.44	3.89
Carbon content (*tonne C/TJ*)	Raw Coal	25.8	26.37	25.8	26.32
	Cleaned Coal	26.8	25.41	26.8	26.32
	Other Washed Coal	26.8	25.41	26.8	26.32
	Briquettes	25.8	33.56	25.8	26.32
	Coke	29.2	29.42	29.2	31.38
	Coke Oven Gas	12.1	13.58	12.1	21.49
	Other Gas	12.1	12.2	12.1	21.49
	Other Coking Products	25.8	29.5	25.8	27.45
	Crude Oil	20	20.08	20	20.08
	Gasoline	18.9	18.9	18.9	18.9
	Kerosene	19.5	19.6	19.5	19.6
	Diesel Oil	20.2	20.2	20.2	20.2
	Fuel Oil	21.1	21.1	21.1	21.1
	LPG	17.2	17.2	17.2	17.2

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[13] Adopted in this research.

	Refinery Gas	15.7	18.2	15.7	20
	Other Petroleum Products	20	20	20	20.2
	Natural Gas	15.3	15.32	15.3	15.32
Oxygenation efficiency (*tonne* CO_2/ton)	Raw Coal	0.98	0.94	1	0.92
	Cleaned Coal	0.98	0.98	1	0.92
	Other Washed Coal	0.98	0.98	1	0.92
	Briquettes	0.98	0.9	1	0.92
	Coke	0.98	0.93	1	0.92
	Coke Oven Gas	0.99	0.99	1	0.92
	Other Gas	0.99	0.99	1	0.92
	Other Coking Products	0.99	0.93	1	0.92
	Crude Oil	0.99	0.98	1	0.98
	Gasoline	0.99	0.98	1	0.98
	Kerosene	0.99	0.98	1	0.98
	Diesel Oil	0.99	0.98	1	0.98
	Fuel Oil	0.99	0.98	1	0.98
	LPG	0.99	0.99	1	0.98
	Refinery Gas	0.99	0.99	1	0.98
	Other Petroleum Products	0.99	0.98	1	0.98
	Natural Gas	0.99	0.99	1	0.99
Emission factor	Raw Coal	2.61	1.9	1.98	1.83
	Cleaned Coal	2.57	2.12	2.05	2.31
	Other Washed Coal	2.57	2.12	2.05	1.33
	Briquettes	2.39	1.93	1.98	1.6
	Coke	2.96	2.85	2.82	2.96
	Coke Oven Gas	8.26	8.55	8.34	11.67
	Other Gas	8.26	6.98	8.34	6.02
	Other Coking Products	4.03	2.86	4.07	2.59
	Crude Oil	3.07	3.08	3.1	3.1
	Gasoline	3.05	3.04	3.11	2.99
	Kerosene	3.1	3.15	3.09	3.1
	Diesel Oil	3.15	3.15	3.15	3.12
	Fuel Oil	3.09	3.05	3.13	3.26
	LPG	2.95	2.95	2.87	3.15
	Refinery Gas	2.82	3.04	2.41	3.38
	Other Petroleum Products	2.9	3.24	3.12	3.12
	Natural Gas	1.91	2.17	1.93	2.16

Appendix B: Grid emission factors

Grid emission factors (as CDM Standardized Baseline)		2014	2015	2016	2017	2018	2019
North China Grid	OM	1.058	1.042	1.000	0.968	0.9455	0.9419
	BM	0.541	0.478	0.451	0.4578	0.4706	0.4819
Northeast China Power Grid	OM	1.128	1.129	1.117	1.1082	1.0925	1.0826
	BM	0.554	0.432	0.442	0.331	0.2631	0.2399
East China Grid	OM	0.810	0.811	0.808	0.8046	0.7937	0.7921
	BM	0.686	0.595	0.548	0.4923	0.3834	0.3870
Central China Power Grid	OM	0.972	0.952	0.923	0.9014	0.8770	0.8587
	BM	0.474	0.350	0.307	0.3112	0.2658	0.2854
Northwest China Power Grid	OM	0.958	0.946	0.932	0.9155	0.8984	0.8922
	BM	0.451	0.316	0.237	0.3232	0.3876	0.4407
Southern China Power Grid	OM	0.918	0.896	0.868	0.8367	0.8094	0.8042
	BM	0.437	0.365	0.307	0.2476	0.1963	0.2135

$$EF = 0.75 \times OM + 0.25 \times BM$$

Appendix C: Entropy Method Code for Stata

```
encode Region, gen(province_n)
xtset province year
xtdes

//Set up positive and negative indicators
global positive_var x6 x10 x11 x12 x17
global negative_var x1 x2 x3 x4 x5 x7 x8 x9 x13 x14 x15 x16 x18 x19
global all_var $positive_var $negative_var

//Normalization
   foreach i in $positive_var{
   qui sum `i'
   gen x_`i'=(`i'-r(min))/(r(max)-r(min))
   }
   foreach i in $negative_var{
   qui sum `i'
   gen x_`i'=(r(max)-`i')/(r(max)-r(min))
   }
//Calculate the proportion of the i^th indicator
   foreach i in $all_var{
   egen `i'_sum=sum(x_`i')
```

```
   gen y_`i'=x_`i'/`i'_sum
   }
   gen n=_N
```

//Calculate the entropy value of the ith indicator

```
   foreach i in $all_var{
     gen y_lny_`i'=y_`i'*ln(y_`i')
     replace y_lny_`i'=0 if x_`i'==0
   }
   foreach i in $all_var{
   egen y_lny_`i'_sum=sum(y_lny_`i')
   }
```

//Calculate the coefficient of variation of the ith indicator d_i

```
   foreach i in $all_var{
   gen E_`i'=-1/ln(n)*y_lny_`i'_sum
   }
  foreach i in $all_var{
   gen d_`i'=1-E_`i'
   }
```

//Calculate the weight of the ith indicator

```
  egen d_sum = rowtotal(d_*)
foreach i in $all_var{
   gen W_`i'=d_`i'/d_sum
   }
```

//Calculate the final score

```
foreach i in $all_var{
   gen Score_`i'=x_`i'*W_`i'
   }
  egen Score = rowtotal(Score_*)
```

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