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Driving factors of carbon emissions from household energy combustion in China

Xinlu Sun [a], Zhifu Mi [a,*], Jin Zhang [b,**], Jinkai Li [c,***]

[a] The Bartlett School of Sustainable Construction, University College London, London, WC1E 7HB, UK
[b] Institute of Industrial Economics, Chinese Academy of Social Science, Beijing, 100032, China
[c] School of Management and Economics, Beijing Institute of Technology, Beijing, 100081, China

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ABSTRACT

Reducing carbon emissions resulting from household direct energy combustion while ensuring equal access to energy is essential for fair transition towards carbon neutrality. In this regard, understanding the driving factors of household direct carbon emissions and projecting future emission pathways are necessary for effective policy implementation. In this study, we applied the logarithmic mean Divisia index model to investigate changes in household direct carbon emissions from 2000 to 2021, and established six scenarios to assess the impacts of energy efficiency improvement and energy transition on carbon reduction. The results showed that the growing household expenditure continuously drives the increase in direct carbon emissions, while the decline in the energy demand per unit household expenditure and energy transition drives the decrease in carbon emissions. Replacing direct energy combustion with electricity is vital to reduce household direct emissions. This study highlights the importance of improving the energy efficiency and promoting the electrification of household energy consumption. Policy interventions should be implemented to facilitate behavioural changes, technology development, and low-carbon infrastructure construction.

1. Introduction

Decarbonizing the household energy demand is vital to global achievement of net zero. Household direct energy demand contributes to 7.7 % of global total energy consumption in 2021 (IEA, IRENA, UNSD, World Bank, WHO, 2023). In this regard, reducing carbon emissions resulting from the household energy demand is an urgent task. As the single largest carbon emitter in the world, China's commitment to carbon neutrality concerns not only its sustainable development but also the global combat against climate change. Currently, household direct energy consumption accounted for 5.1 % of China's total energy consumption in 2021. The proportion is larger in high-income countries, e.g., 7.3 % in Japan, 8.1 % in the United States and 22.9 % in the United Kingdom (IEA, 2023). Consequently, household direct carbon emissions are an important source of the total emissions. For example, approximately 6.4 % of the carbon dioxide emissions in the United States originates from household direct use of fossil fuels for cooking, heating and cooling (EIA, 2023). This is partly attributed to the growing energy demand with affluence because the lifestyle of people tends to be carbon intensive, for example, extensive use of heating appliances. In addition, consistent efforts to improve the life conditions of the poor have led to increased carbon emissions. In China, direct household energy consumption increased by 218.3 % from 2002 to 2016 (Zhou and Gu, 2020). Therefore, household direct emissions are probably going to increase as income rises in the future (Wiedmann et al., 2020).

Reducing household direct carbon emissions is challenging considering the increasing energy demand and engagement of the enormous population. On the one hand, improving life conditions and ensuring a decent lifestyle and affordable energy remain China's priorities for sustainable development. Similar to other developing countries, biomass dominates the cooking energy supply in rural China (Zheng et al., 2014; Zou and Luo, 2019). The household direct fuel consumption is about 0.33 t per capita in China, much lower than that in high-income countries (e.g., 0.74 t per capita in the United States, excluding biomass and gasoline) (EIA, 2023). On the other hand, reducing household direct carbon emissions involves multiscale efforts, including national

* Corresponding author. The Bartlett School of Sustainable Construction, University College London, London, WC1E 7HB, UK.
** Corresponding author. Insititute of Industrial Economics, Chinese Academy of Social Sciences, Beijing, 100032, China.
*** Corresponding author. School of Management and Economics, Beijing Institute of Technology, Beijing, 100081, China.
E-mail addresses: z.mi@ucl.ac.uk (Z. Mi), echozhang0817@foxmail.com (J. Zhang), lijinkai@sina.com (J. Li).

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strategic plans, effective policy implementation by local authorities and deep participation of communities and households. Residents may lack knowledge of the importance of reducing carbon emissions and may be unaware of approaches to reducing carbon emissions. To reduce carbon emissions, residents should improve the energy efficiency of household appliances, but people may be reluctant due to the additional costs. In addition, community-level carbon reduction requires support in the form of infrastructure construction. For example, the use of electric vehicles requires access to charging facilities. The increasing energy demand and challenge of motivating people make the decarbonization of household energy consumption more difficult.

Understanding the driving factors of carbon emissions resulting from household energy combustion and its trends in the future is essential for fair and resilient transition towards carbon neutrality in China. Different socioeconomic indicators may drive the change in carbon emissions in different ways. Knowledge of the impact of factors provides guidance for policy interventions to target key segments. In addition, projecting the trajectory of carbon emissions in the future under various decarbonization scenarios could elucidate the additional energy demand and carbon emissions associated with economic growth. Such information could better assist policymakers in paving the way for the decarbonization of household energy consumption as soon as possible, including enacting related policies and investing in low-carbon industries. In this regard, some studies have shed light on the key factors that drive changes in household energy consumption and related carbon emissions (Chen et al., 2018; Guo et al., 2017; Ma et al., 2016; Zhang and Bai, 2018).

However, due to a lack of the latest data, the recent trend in the determinants of household direct emissions is yet to be explored. In addition, projections of the future trajectories of household direct emissions under different decarbonization strategies have not been reported. This study contributes to this field by introducing the latest changes in the driving factors of household direct emissions and projecting emission pathways under several decarbonization scenarios. In contrast to implementing mandatory measurements and providing economic incentives to reduce the carbon emissions along the supply chain and power generation, reducing direct emissions resulting from household fuel combustion is difficult because this depends on the engagement of communities and the facilitation of behavioural changes among consumers. One case is the extensive energy demand for cooking. People spend more time on and use more energy for cooking because of China's culinary culture (Zheng et al., 2014). Such cultural contexts influence proactive and spontaneous shifts in energy consumption behaviours.

In this study, we first investigate the driving factors of household direct carbon emissions from 2000 to 2021 using logarithmic mean Divisia index (LMDI) analysis. Carbon emissions from household direct combustion of fossil fuels and other energy sources are considered. The six driving factors include carbon efficiency by energy type, energy structure, energy intensity of expenditure, expenditure per capita, urbanization and population. Based on historical trends, we project the future trajectories of household direct carbon emissions under several scenarios. These scenarios are established to simulate the effectiveness of different decarbonization strategies, mainly referring to energy efficiency improvement and energy mix upgrades. Consequently, the study results can offer insights into low-carbon transition of the household energy demand in China. It assists policymakers in providing residents with reasonable and affordable energy while simultaneously reducing climate impacts.

2. Methods

2.1. Logarithmic mean divisia index model

Following previous studies, we decompose household direct carbon emissions into six factors (Ding and Li, 2017; Ma et al., 2016; Wang et al., 2021; Zheng et al., 2020), as expressed by Eq. (1):

$$C^t = \sum_{i,j} \frac{C_{ij}}{E_{ij}} \bullet \frac{E_{ij}}{E_i} \bullet \frac{E_i}{EXP_i} \bullet \frac{EXP_i}{POP_i} \bullet \frac{POP_i}{POP} \bullet POP$$

$$= \sum_{i,j} c_{ij} \bullet s_{ij} \bullet e_i \bullet x_i \bullet u \bullet p \quad (1)$$

where C_{ij} denotes the carbon emissions and subscript i denotes the population category, with 1 denoting urban residents and 0 denoting rural residents, and j denotes the different energy types. E_{ij} and E_i are the household energy consumption in standard coal equivalent units. EXP_i is the annual expenditure of rural or urban residents. POP_i and POP are the national populations. Based on Eq. (1), household direct carbon emissions can be divided into the following six factors.

1) $c = C_{ij}/E_{ij}$ is the carbon emission intensity of energy type j, indicating the carbon content in coal, oil, gas and other energy sources.
2) $s = E_{ij}/E_i$ is the proportion of the consumption of energy type j, indicating the energy structure.
3) $e = E_i/EXP_i$ is the total energy demand per unit of the total monetary expenditure, indicating the energy intensity of residential expenditure.
4) $x = EXP_i/POP_i$ is the annual expenditure per capita, indicating the purchasing power of urban and rural residents.
5) $u = POP_i/POP$ is the proportion of the rural or urban population, indicating urbanization.
6) P is the population.

Note that household direct carbon emissions result from the combustion of coal, oil, gas and other energy sources, but j can also represent heat and electricity, of which the carbon content is set to 0 because indirect emissions are not accounted for in this study.

Hence, the change in household direct carbon emissions ΔC^t in year t relative to the previous year t-1 can be calculated with Eqs. (2) and (3):

$$\Delta C^t = \sum_{i,j} L\left(w_{ij}^t, w_{ij}^{t-1}\right) \ln\left(c^t / c^{t-1}\right) + \sum_{i,j} L\left(w_{ij}^t, w_{ij}^{t-1}\right) \ln\left(s^t / s^{t-1}\right)$$

$$+\sum_{i,j} L\left(w_{ij}^t, w_{ij}^{t-1}\right) \ln\left(e^t / e^{t-1}\right) + \sum_{i,j} L\left(w_{ij}^t, w_{ij}^{t-1}\right) \ln\left(x^t / x^{t-1}\right)$$

$$+\sum_{i,j} L\left(w_{ij}^t, w_{ij}^{t-1}\right) \ln\left(u^t / u^{t-1}\right) + \sum_{i,j} L\left(w_{ij}^t, w_{ij}^{t-1}\right) \ln\left(p^t / p^{t-1}\right)$$

$$= \Delta C_c{}^t + \Delta C_s{}^t + \Delta C_e{}^t + \Delta C_x{}^t + \Delta C_u{}^t + \Delta C_p{}^t \quad (2)$$

$$\text{where } L\left(w_{ij}^t, w_{ij}^{t-1}\right) = \left(C_{ij}^t - C_{ij}^{t-1}\right) \Big/ \left(\ln\left(C_{ij}^t\right) - \ln\left(C_{ij}^{t-1}\right)\right) \quad (3)$$

Therefore, changes in household direct carbon emissions can be divided into six factors. ΔC_c^t, ΔC_s^t, ΔC_e^t, ΔC_x^t, ΔC_u^t, and ΔC_p^t denote the emission changes driven by the carbon emission intensity, energy mix, energy consumption intensity, per capita expenditure, urbanization and population variation, respectively. Regarding the energy mix, the consumption of fossil and nonfossil fuels is calculated in standard coal equivalent units, with only emissions resulting from the combustion of fossil fuel and other energy sources accounted for here.

Carbon emissions resulting from fossil fuel combustion C_{ij} and other energy usage C_{io} of urban and rural households are calculated based on the latest IPCC refinement of the guidelines for national greenhouse gas inventories (Buendia et al., 2019; Eggleston et al., 2006), expressed in Eqs. (4) and (5):

$$C_{ij} = D_{ij} \times N_j \times H_j \times O_j \quad (4)$$

where D_{ij} denotes the unit fossil fuel consumption, with missing or double accounting avoided. $N \times H \times O$ are the emission factors for fuel combustion, calculated by three product terms, namely, the net calorific value measuring the heat released per unit of fossil fuel (N), the carbon content representing the CO_2 emitted per unit of released (H), and the oxidization rate of fossil fuel combustion (O).

Carbon emissions released from usage of other energy, C_o, can be calculated as:

$$C_{io} = D_{io} \times T \tag{5}$$

where D_{io} denotes the unit consumption of other energy sources and T is the emission factor for solid biomass fuel because biomass is the main energy type in the category of other energy sources. Following the literature (Peng et al., 2019; Zhang et al., 2018), we use the average value of the emission factors of wood and crop residue combustion weighted by the fuel distribution and stove type (traditional stoves, improved stoves, kangs, braziers and household boilers).

2.2. Emission pathways and household carbon reduction scenarios

We developed six emission reduction scenarios to project the emission pathway induced by household energy combustion. The projection is based on Eq. (6):

$$C^t = \sum_{i,j} c_{ij}{}^t \bullet s_{ij}{}^t \bullet e_i{}^t \bullet x_i{}^t \bullet u^t \bullet p^t$$

$$= \sum_{i,j} \left(c_{ij}{}^{2021} \alpha c_{ij}{}^t\right) \bullet \left(s_{ij}{}^{2021} \alpha s_{ij}{}^t\right) \bullet \left(e_i{}^{2021} \alpha e_{ij}{}^t\right) \bullet \left(x_i{}^{2021} \alpha x_{ij}{}^t\right) \bullet \left(u^{2021} \alpha u_{ij}{}^t\right) \bullet \left(p^{2021} \alpha p_{ij}{}^t\right)$$

$$= \sum_{i,j} C^{2021} \bullet \alpha c_{ij}{}^t \alpha s_{ij}{}^t \alpha e_{ij}{}^t \alpha x_{ij}{}^t \alpha u_{ij}{}^t \alpha p_{ij}{}^t \tag{6}$$

Where the superscript t denotes the year, αc, αs, αe, αx, αu, and αp represent the change rate in each of the six determinants. With the household direct emissions in 2021 and assumptions of changes in each of the six factors in year t relative to 2021, we can estimate the household direct carbon emissions in year t. Here, we use energy-related indicators to refer to the former three indicators, including carbon efficiency by energy type, energy structure, energy intensity of expenditure. The changes in energy-related indicators, derived from assumptions of energy mix transition and reduction in energy intensity of expenditure, are used for the emission reduction scenarios. We use socioeconomic indicators to refer to the latter three indicators, including expenditure per capita, urbanization and population. These indicators are considered for the socioeconomic pathway in each scenario. The description of the scenarios are as follows and in Table 1.

We applied shared socioeconomic pathway 2 (SSP2) to determine the socioeconomic parameters αx, αu, and αp. SSPs were developed by the IPCC as a series of scenarios depicting possible pathways for future socioeconomic and economic development and subsequently investigating the impact of socioeconomic development characteristics on carbon emissions and climate change. Among the five pathways, the so-called Middle of the Road scenario SSP2 is mostly used as the business-as-usual scenarios (Bauer et al., 2017). Therefore, we refer to the SSP2 to describe moderate population growth and moderate economic development. We used the growth rate of the per capita GDP as a proxy to project the increase in the per capita household expenditure, namely, αx (Jing et al., 2020). Changes in urbanization αu and population αp were obtained from the literature (Chen et al., 2020).

Table 1
Scenario settings.

Socioeconomic pathway: SSP2 adopted		
Emission reduction: assumptions about energy demand and energy transition		
	Energy demand	
Energy transition	SL low energy demand	SH: high energy demand
	SL_gas: plus replacement of coal with gas	SH_gas: plus replacement of coal with gas
	SL_elect: plus replacement of fossil fuel with electricity	SH_elect: plus replacement of fossil fuel with electricity

Under the six decarbonization scenarios, we assumed different strategies to mitigate the carbon emissions induced by household direct fossil fuel combustion. In this regard, reducing the energy demand per unit of household expenditure and promoting the transition of the household energy mix are the two main approaches. In simulating the energy demand per unit of household expenditure, two scenarios were developed, namely, a low energy demand per unit of household expenditure (shortened as low energy demand) and a high energy demand per unit of household expenditure. In simulating the transition of the household energy mix, two scenarios were developed, namely, replacing coal with gas and replacing fossil fuel with electricity. Based on the two energy demand scenarios and with the combination of the energy demand scenarios and energy mix transition scenarios, we obtained six decarbonization scenarios in total.

Under the low energy demand scenario (SL), changes in αe were set to the maximum historical value of the energy intensity reduction rate, while αc and αs remained unchanged, at 1. This represents the lowest energy demand growth and fastest energy efficiency improvement. Under the high energy demand scenario (SH), we used the decrease rate of the energy intensity per unit of the GDP as a proxy for the changes in the energy consumption per unit of household expenditure. Under this scenario, αc and αs remained unchanged, at 1.

Based on the two scenarios of energy demand changes, two transition schemes of the energy mix were developed. Replacing coal with gas indicates phasing out household coal usage and replacing it with natural gas. With such energy mix transition assumptions, we designed two scenarios, namely, SL_gas and SH_gas, which have consistent assumptions with those under SL and SH, respectively. Currently, the direct coal consumption of urban residents has nearly been eliminated; therefore, these scenarios mainly investigate the effect of energy transition in rural areas. Replacing fossil fuel with electricity indicates phasing out household direct consumption of fossil fuels. The consumption of fossil fuels, namely, coal, gas and oil, is gradually being transferred to electricity, with complete transition achieved by 2060. Similarly, there were two scenarios, SL_elect and SH_elect.

2.3. Data sources

The data used in this study are all publicly accessible. The socioeconomic data are derived from the National Bureau of Statistics. Carbon emission inventories are not officially published. We therefore use the national energy balance sheet to derive household energy consumption data from the National Statistical Yearbook to establish China's household direct carbon emission inventories. The emission factors are derived from previous studies (Mi et al., 2017; Zheng et al., 2019).

3. Results

3.1. Trends of household direct carbon emissions

Household direct carbon emissions in China reached 518.2 Mt in 2021, increasing from 199.4 Mt in 2000 (Fig. 1). Overall, household direct carbon emissions account for 5.1 % of the total territorial carbon emissions. In 2021, household direct carbon emissions reached 0.37 t per capita, less than those in high-income countries. In the United States, carbon emissions resulting from residential direct combustion of natural gas and petroleum (excluding petroleum for transport) reached 1.0 t per capita (EIA, 2023). As the economic development and purchasing power of Chinese residents increase, lifestyles may become more energy intensive and induce higher carbon emissions in the future. In recent

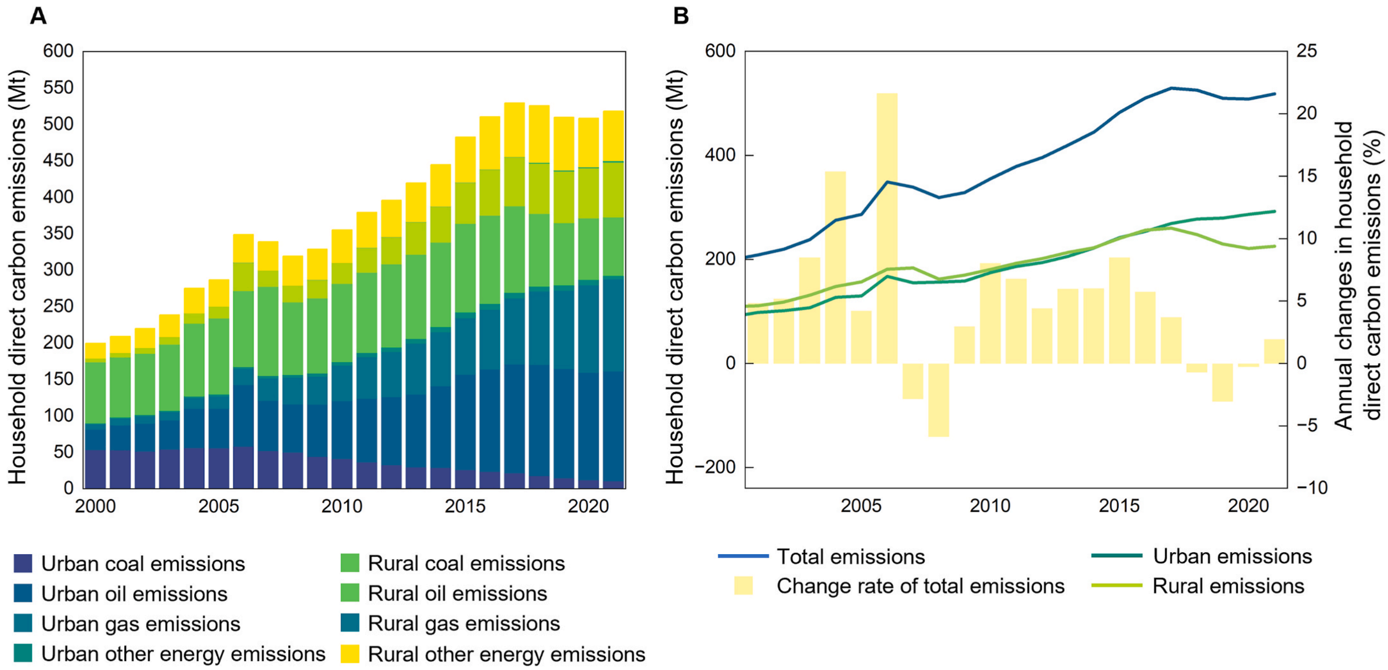

Fig. 1. Trends of the household direct carbon emissions in 2000 and 2021. A. Urban and rural household carbon emissions by source (coal, oil, gas and other energy). B. Total, urban and rural household carbon emissions and annual change rate.

years, household direct carbon emissions have plateaued since 2017. In 2017, household direct carbon emissions reached 529.3 Mt, representing the highest annual emissions thus far. Thereafter, carbon emissions slightly decreased and rebounded in 2021. This was accompanied by continuously growing urban carbon emissions and decreasing rural carbon emissions after 2017. Carbon emissions stemming from urban households have been increasing for decades. In 2021, urban residents produced 292.6 Mt of carbon emissions, mainly due to their consumption of natural gas and oil. Rural residents caused 225.6 Mt of carbon emissions mainly because of the consumption of coal, oil and other energy. The direct carbon emissions of urban and rural residents are 0.32 and 0.46 t per capita, respectively.

Regarding the energy sources of carbon emissions, the usage of natural gas is the main source for urban residents, while oil is the main source for rural residents. The access to gridded natural gas among urban residents has been greatly improved since the beginning of this century, attributed to efforts in energy infrastructure construction. In 2000, carbon emissions resulting from natural gas combustion reached only 7.0 Mt, accounting for only 7.7 % of the total urban direct carbon emissions. A transition in the urban energy structure over the past two decades, manifested as the usage of natural gas, caused 126.1 Mt of carbon emissions, accounting for 43.1 % of the total urban direct emissions in 2021. This has helped China move towards low-carbon heating and cooking by eliminating urban direct coal combustion. For rural residents, coal remains one of the main energy types. Carbon emissions resulting from direct coal usage in rural China reached 80.3 Mt in 2021. The proportion of carbon emissions resulting from coal usage in the total rural emissions has greatly declined from 76.7 % in 2000 to 35.6 %, indicating that the dominant role of coal in the rural energy supply has greatly changed. However, phasing out coal in rural areas is difficult because of the energy consumption behaviour and the difficulty in establishing natural gas grids. The diffuse distribution of residences in rural areas, compared with the compact distribution of city residences, leads to notable difficulty and dramatically increases the cost of infrastructure construction for rural natural gas grids. Instead, oil, specifically liquefied petroleum gas, becomes important for the rural cooking energy demand. Gasoline, another type of oil fuel, is another major source of carbon emissions, mainly from the usage of private vehicles. Due to the increasing private car ownership in China, the consumption of gasoline and associated carbon emissions have increased.

3.2. *Driving factors of the changes in household direct carbon emissions*

The driving factors of the changes in household direct carbon emissions can be grouped into two categories: energy factors and socioeconomic factors. Energy factors include carbon intensity (c), energy structure (s), and energy demand per unit of household expenditure (e); socioeconomic factors include per capita household expenditure (x), urbanization (u) and population (p). From 2000 to 2021, the household direct carbon emissions increased by 159.9 %, and the abovementioned six factors drove these changes by −2.2 % (c), −72.1 % (s), −70.2 % (e), 289.6 % (x), −5.8 % (u) and 20.4 % (p), respectively (Fig. 2). In the long term, energy factors and urbanization drive the decline in household direct carbon emissions, while the other socioeconomic factors facilitate growth.

3.2.1. *Expenditure per capita and energy intensity of expenditure*

The per capita household expenditure is the major factor contributing to the increase in direct carbon emissions. From 2000 to 2021, the per capita household expenditure has driven the growth in emissions from direct fossil fuel combustion (289.6 %). The growth in expenditure indicates people's affluence and their increased demand for energy, for example, more electric appliances and private vehicles are used. Regarding household expenditure, a significant gap between urban and rural expenditures exists (Fig. 3). In 2021, the urban household expenditure was 37.1k yuan per capita, robustly rebounded from the level in 2020 (33.7k yuan per capita). The rural household expenditure was only 18.8k yuan per capita, increased from the value of 16.3k yuan per capita in 2020. In 2020, the decrease in the urban household expenditure was possibly related to the lockdown measures due to COVID-19. A mitigation of the very large gap between rural and urban consumption has been observed over the past two decades. At the beginning of this century, the urban−rural gap was larger, with the annual per capita expenditure of urban residents reaching 10.6k yuan while that of rural residents reached 3.2k yuan. The rural per capita expenditure accounted

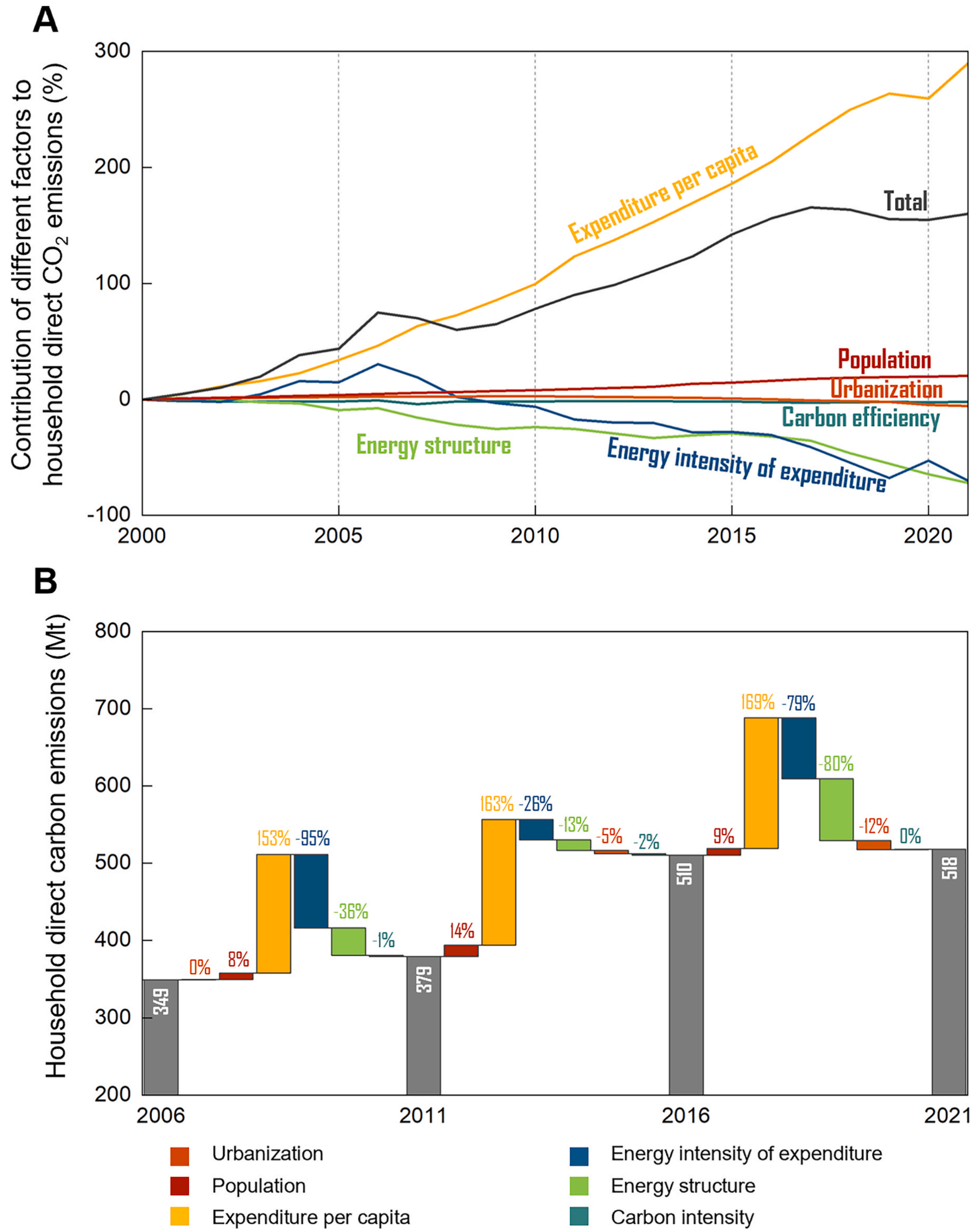

Fig. 2. Trends of the drivers of household direct carbon emissions. A. Contributions of the different factors to the changes in the household direct carbon emissions from 2000 to 2021, adopting 2000 as the base year. B. Absolute contributions of the different factors to the changes in the household direct carbon emissions from 2006 to 2021.

for only 30.3 % of the urban per capita expenditure. From 2013 to 2018, the household expenditure of rural residents has increased at an annual rate ranging from 9 % to 12 %, while the urban household expenditure has increased at a rate of approximately 6 %. In 2021, the urban household expenditure was almost twice the rural household expenditure. Continuous efforts in narrowing the urban–rural imbalance constitute one of the main targets of sustainable development in China in the coming years. In addition, economic development could enhance the private purchasing power and therefore increase the average level of the future household energy demand.

As per capita expenditure increases, marginal energy demand of household expenditure decreases. Therefore, the declining energy demand per unit of household expenditure contributes to the decrease in household direct carbon emissions. Specifically, the energy demand per

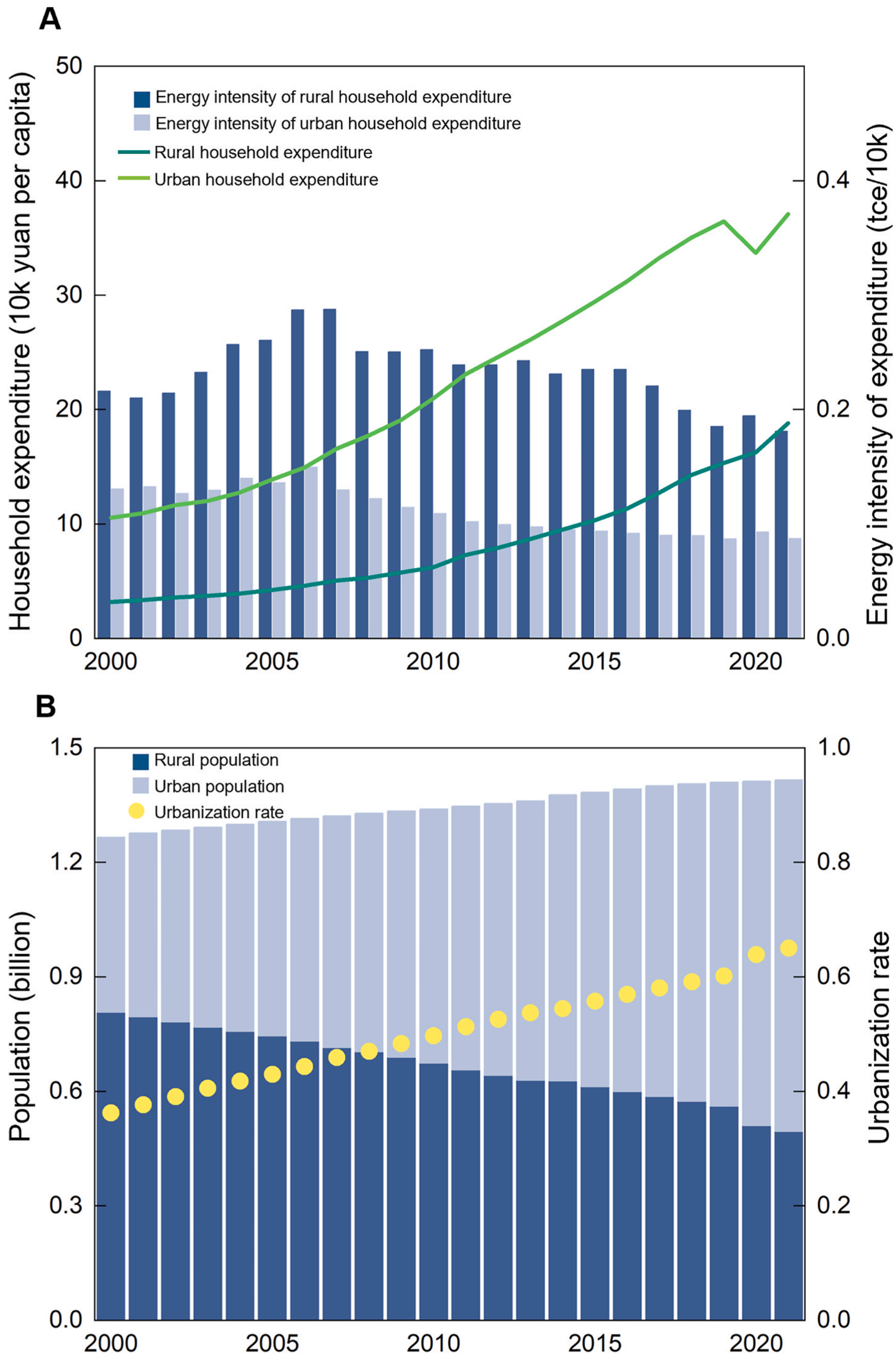

Fig. 3. Urban and rural household energy consumption levels, expenditures, and populations. A. Urban and rural household expenditures and energy demands per unit of expenditure. B. Urban and rural populations.

unit of household expenditure has continuously driven the decrease in carbon emissions since 2007, except for the slightly reversed contribution in 2020. The energy intensity of household consumption decreased from 13.1 to 8.7 kg/k yuan for urban residents and decreased from 21.6 to 18.1 kg/k yuan for rural residents between 2000 and 2021. The energy demand per unit of household expenditure continuously decreased, which indicates that the growth in the household expenditure is faster than that in energy demand. This suggests that household energy spending is a type of necessity (Meier et al., 2013) and therefore, the marginal energy demand of household expenditure decreased. In other words, the growth in direct carbon emissions will gradually peak and plateau regardless of the continuous increase in household expenditure.

Although the energy intensity of rural residents is higher than that of urban residents, this does not necessarily demonstrate that rural lifestyles are more energy intensive than urban lifestyles. Considering the lower expenditure and energy demand per capita of rural residents, this indicates that the cost of the energy demand accounts a larger proportion of the rural household expenditure. Considering and burden of energy costs and that demand in energy is less elastic than the non-necessity goods for households, rural residents are relatively more vulnerable to energy price shocks.

3.2.2. *Energy structure*

The shift in the energy mix is another important contributor to the low-carbon transition of household energy consumption and the decline in household direct carbon emissions. Since 2000, the energy mix has gradually contributed to a 72.1 % decrease in carbon emissions. Before 2017, the contribution of the energy mix increased at a moderate rate of −2.7 % per year. Between 2017 and 2021, the annual contribution to emission reduction was −10.8 %. The predominant supply of coal for urban and rural energy consumption at the beginning of this century has been systematically changed, and the current energy consumption is more notably oriented towards diversification and low carbon emissions (Fig. 4). Urban and rural consumption of coal reached 25.6 and 39.1 Mt in 2000, respectively, accounting for 36.9 % and 78.3 % of the total energy demand, respectively. With efforts in greening the household energy consumption, the supply of coal for urban residents has been shifted to other energy types since 2007. The urban consumption of coal in 2021 reached 5.3 Mt, only accounting for 2 % of the total energy consumption. Electricity, oil, gas and heat all play important roles in urban energy consumption, accounting for 27.4 %, 26.2 %, 26.0 %, and 18.1 %, respectively, of the total energy consumption in 2021. The energy mix in rural areas largely differs from that in urban areas. Although the contribution has been greatly reduced, coal remains one of the main energy sources in rural areas, accounting for nearly a quarter (22.4 %) of the total energy consumption, and the level of coal consumption (37.8 Mtce) matched that in 2000. With very limited access to gridded natural gas and heat, electricity is the predominant energy source for rural residents. In 2021, the rural consumption of electricity was 69.1 Mtce, accounting for 41.0 % of the total energy consumption. Electrification in rural areas is driving the decline in rural direct carbon emissions. Oil accounts for 22.9 % of the total energy consumption in rural areas in 2021, becoming the second principal energy type. An obvious difference between the rural and urban energy mixes is the usage of other energy sources in rural areas. Biomass, as the main energy type in the category of other energy sources, accounted for 13.0 % of the total energy demand in rural China in 2021. Derived from biomass residues, including firewood and crops, biomass energy is often used for domestic cooking and heating (Xu et al., 2022). Despite its nature as a renewable energy source, biomass combustion in rural areas exhibits a very low energy conversion efficiency and can lead to health risks.

3.2.3. Carbon intensity, urbanization and population

Changes in the carbon intensity, urbanization and population over the past two decades have resulted in fewer changes in carbon emissions than those induced by changes in the abovementioned three major factors. Even though the carbon emission factors of the 17 energy types remained constant in the study period, the carbon intensity of coal, gas and oil slightly changed. The growth in the population gradually drove the increase in household direct carbon emissions by 20.4 % from 2000 to 2021. Urbanization contributed to the increase in direct carbon emissions because of the occurrence of impoverishment in rural areas before 2016. Since 2017, the role of urbanization has reverted regarding its contribution to carbon emissions. As the energy demand increases in both rural and urban areas, the impact of the lower energy efficiency in rural areas on the emission intensity increases. Therefore, urbanization has caused a decrease in direct carbon emissions in recent years. Over the past two decades, the urbanization rate increased from 0.36 to 0.65, indicating that rural residents are moving to urban areas in the pursuit of better employment opportunities and life conditions. On the one hand,

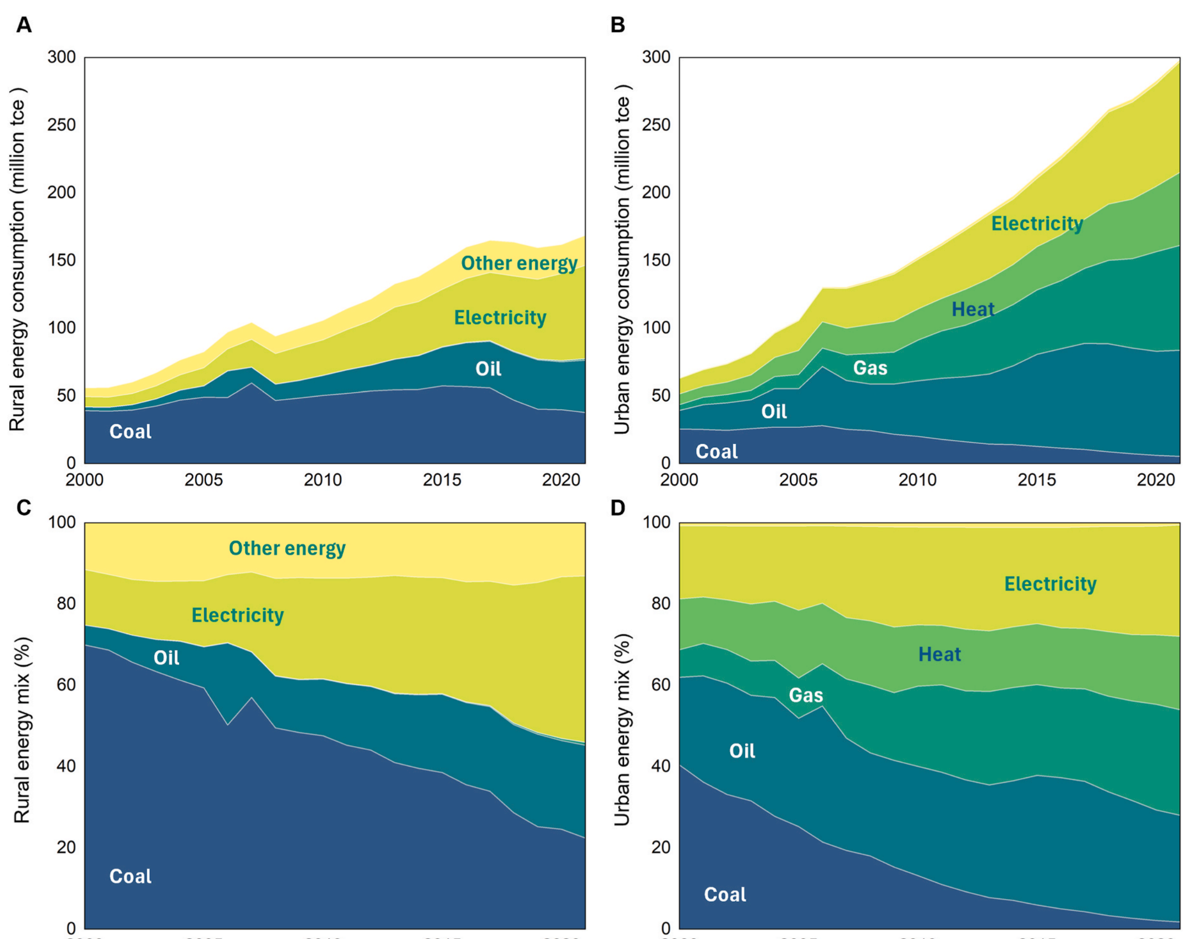

Fig. 4. Household energy consumption by source and energy mix from 2000 to 2021. A. Rural energy consumption. B. Urban energy consumption. C. Rural energy mix. D. Urban energy mix.

the urbanization rate will grow in the future, requiring further energy infrastructure to ensure energy access among new urban residents and therefore increasing the pressure on low-carbon energy transition. On the other hand, the contribution of urbanization to household direct carbon emissions is moderate and even smaller than that of population, indicating small differences in the carbon emissions per capita between urban and rural residents. This can be explained by the higher energy efficiency of urban residential consumption, although urban residents have higher expenditures.

The outbreak of COVID-19 in 2020 induced changes in the driving factors of household direct carbon emissions despite their stable long-term contribution. These changes may be minor but could have paved the way for long-term changes; therefore, necessary intervention should be implemented to avoid further negative impacts. It was revealed that the per capita household expenditure contributed less to emission growth, but the energy intensity of household expenditure contributed to an increase in carbon emissions in 2020. This indicates that the marginal energy consumption of household expenditure after the COVID-19 outbreak increased. In other words, the growth in the per capita household expenditure declined, but the energy expenditure increased. On the one hand, the halted economic activities and implemented measures in response to COVID-19 during the first half of 2020 led to a recession in economic growth, and therefore, the consumption willingness was not recovered. On the other hand, due to the lockdown and travel restrictions, people spent more time at home, and the demand for household direct energy consumption increased associated with cooking, heating and cooling, lighting, etc. These two factors jointly drove household expenditure towards an energy-intensive pattern in 2020. Specifically, the average household expenditure of urban residents decreased by 7 %, but the energy intensity of expenditure increased by 7 %. The reversed contribution of the two factors recovered in 2021, and the robust rebound in expenditure drove the increase in total emissions. Although the lockdown measures were temporary and economic activities were restored, COVID-19 may exert a long-term impact by influencing household preferences for fossil fuel and energy consumption choices.

3.3. Projection of future emission pathways

The scenarios of enhanced carbon reduction efforts were established based on emission reduction strategies from both the demand and supply sides (Fig. 5). Scenarios SH and SL simulate high energy demand and low energy demand, respectively. Under scenario SH, a moderate decline rate of the marginal energy consumption was assumed to reduce the energy demand per unit household expenditure, while under scenario SL, a high decline rate of the marginal energy consumption was assumed. Household direct carbon emissions first increased and then peaked in 2030 at 577.7 Mt in the scenario SH. This conforms with the national carbon peak target. By 2060, household carbon emissions were reduced to 251.9 Mt under scenario SH, which is 48.6 % of the volume in 2021. Under this scenario, the reduction rate of the carbon intensity of the GDP was employed. Considering that the increase in household expenditure was projected by the growth rate of the GDP, this could represent a moderate decline in the energy demand per unit of household consumption. Although direct carbon emissions will be greatly reduced according to the high energy demand assumption in SH, further efforts are still needed to achieve carbon-neutral energy consumption. Under scenario SL, the historically maximum rate of marginal energy consumption reduction is adopted to project changes in energy demand in the future (7.6 % and 8.5 % for urban and rural residents, respectively, adjusted by the consumption-to-GDP ratio in accordance with assumption in expenditure). With faster reduction in the marginal energy consumption, household direct carbon emissions will be greatly reduced to 127.2 Mt, which is only a quarter of the current level. The requirement to reduce the marginal energy consumption necessitates proactive energy reduction actions by households and consumers to transition their high carbon lifestyles into sustainable and responsible consumption behaviours.

The other four scenarios show the contribution of the transition in the energy mix to household direct emissions reduction. Under scenarios SH_gas and SL_gas, phasing out household direct combustion of coal and replacing coal with natural gas, respectively, are assumed. By 2060, coal to natural gas transition can lead to an annual reduction in carbon emissions of 2.6 % under SH_gas and 3.0 % under SL_gas. Due to gas pipeline and grid construction, coal usage in urban areas has been replaced by natural gas in recent years. Scenarios SH_gas and SL_gas hence mainly involve the assumption of rural residents' full access to gridded natural gas. The limited effect of emission reduction does not suggest the failure of improving natural gas accessibility for decarbonization. This is due to the rapid urbanization according to socioeconomic assumptions. With the development in real estate and infrastructure construction, the rural population continues to move to urban areas and therefore results in increased difficulty in building rural natural gas grids considering the cost and benefits. From the perspective of carbon

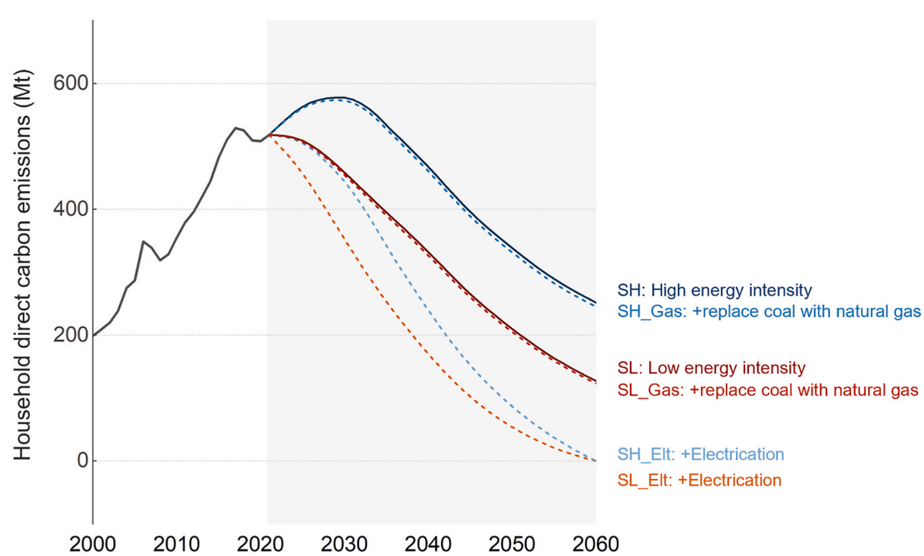

Fig. 5. Historical and projected carbon emissions from household energy combustion. Note: energy intensity in scenarios SH and SL indicates energy consumption per unit of household expenditure.

reduction, rural access to natural gas cannot be fully justified if rural residents are moving to cities.

Scenarios SH_elect and SL_elect simulate the effect of end-use electrification on reducing direct carbon emissions. As indirect carbon emissions, i.e., emissions resulting from power generation, are not considered in this study, electrification plays a very important role in eliminating household direct combustion of fossil fuels. Under both scenarios, the direct emissions can be reduced to zero by electrification. Under SH_elect, the total carbon emissions between 2022 and 2060 can be reduced by 44.1 %, and under SL_elect, the total carbon emission reduction can reach 39.8 %. This can greatly mitigate the climate impact of household direct combustion of fossil fuels and reduce the relative health impacts. On the one hand, these results indicate that electrification becomes increasingly significant in reducing household direct emissions when energy efficiency improvement progresses to a lower degree, as assumed under SH_elect. On the other hand, if the household energy demand per unit expenditure can be greatly reduced, this could reduce the pressure on the residential power supply. Overall, decarbonizing power generation and facilitating household willingness to systematically change to electricity are vital to reduce the total carbon emissions under the above two scenarios.

4. Discussion

The household direct carbon emissions in China peaked in 2017 but rebounded in 2020. The growing household expenditure continuously drives the increase in direct carbon emissions, while the decline in the energy demand per unit household expenditure drives the decrease in carbon emissions. These two predominant factors contribute to the growth in direct carbon emissions, indicating that lifestyles are becoming energy intensive because of the upturn in living standards. Currently, the energy consumption per capita in China continues to increase. Although the purchase of electric appliances and the development of renewable energy could reduce the carbon intensity of household expenditures, the reduction in direct fossil fuel combustion usually encounters difficulty. For example, carbon emissions resulting from household natural gas and petroleum usage have plateaued for decades in the United States (EIA, 2023). With a reduction in electricity-induced indirect emissions, direct emissions account for a larger proportion of the total household energy-related carbon emissions in the United States. This demonstrates the necessity of additional efforts to reduce household direct carbon emissions.

Upgrades in the energy mix also contribute to the decarbonization of household energy consumption. Over the past two decades, electricity usage has increased by 741 % for rural residents and 564 % for urban residents. The proportion of electricity consumption to the total energy demand increased from 13.7 % in 2000 to 41.0 % in 2021 in rural areas and from 18.0 % to 27.4 % in urban areas. Coal consumption has been replaced by other energy types, e.g., natural gas, heat, and electricity, in urban areas. In many cities, natural gas is the main energy source of heating and cooking, where infrastructure construction yields a notable contribution. While phasing out coal combustion in cities, rural residents still suffer from limited access to clean and climate-responsible energy. Coal consumption in rural areas has gradually decreased but still accounts for a quarter of the total energy demand. The movement of the rural population into urban settlements further reduces the benefits and motivation for large-scale infrastructure construction while also offering opportunities to build home renewable energy systems. Overall, despite the full access to electricity in 2013 in China (IEA, 2023), residential reliance on fossil fuel combustion is still a major issue. Decarbonization through both production- and consumption-side energy transitions should be facilitated.

The household energy demand will continuously grow in the future. Both affluence and urbanization drive the increase in the energy demand. Increased wealth enables residents to use more energy to improve their life conditions, for example, the usage of electric appliances, fossil-fuel-based cooking and heating equipment, and private vehicles. For rural residents and the lowest-income group in the poor regions, the energy demand will likely grow considering regional disparities (He et al., 2023; Mi and Sun, 2021). One example is the usage of air conditioners. The electricity consumption of air conditioners and fans for cooling accounts for approximately 20 % of the total electricity used in buildings. In China, 60 % of households are equipped with air conditioners, while in some high-income countries, air conditioners are available in 91 %, 90 % and 86 % of households in Japan, the United States and South Korea, respectively (IEA, 2018). According to the projection by the International Energy Agency, the air conditioner stock in China will almost double by 2050 over the level in 2020 (730 million units). The increasing car ownership will also cause a growing gas and oil demand. In 2016, vehicle ownership in China reached 216 units per 1000 people, which is much lower than that in high-income countries (867 vehicles per 1000 people in the United States) (World Health Organization, 2016). In this regard, household energy consumption will increase due to the increased demand for cooling and transport.

5. Conclusion and policy implications

The findings in this study indicate that future carbon reduction should be achieved based on the reduction in the marginal energy consumption, improvement in energy efficiency, electrification of household direct energy use, and technological innovation in renewable energy. Preventing lifestyles from becoming more energy intensive requires accelerated efforts to reduce the marginal energy consumption, i.e., energy consumption per unit household expenditure. Economic incentives can be implemented to raise individual motivation to transit their lifestyle. Beyond the behavioural changes underpinned by economic benefits, a low-carbon lifestyle should be accompanied by a shift in social norms. In this process, publicity-generating activities and policy interventions could be helpful in raising public awareness of the importance of individual transitions in the global combat against climate change. Specifically, the low-carbon behaviour of the high-income group yields a potentially greater impact because carbon emissions sharply increase with income (Mi et al., 2020; Sun et al., 2022). In addition, improving the energy efficiency is critical to reduce energy consumption. For example, improving the efficiency of air conditioners through technological innovation could help reduce the future energy demand for space cooling by half (IEA, 2018). As the life conditions of low-income and rural residents are improved, a decent life should be guaranteed by providing affordable and climate-responsible energy. Decarbonizing the additional energy demand resulting from poverty and inequality reduction requires improving the energy efficiency rather than constraining energy consumption.

Promoting the electrification of household energy usage along with decarbonizing power generation substantially contribute to reducing future household direct carbon emissions. Electrification is assumed to cause a reduction in the total carbon emissions by nearly half and to provide more benefits for residents. Appropriate usage of electric appliances could result in an improvement in the energy efficiency of household energy demand (Hammerle and Burke, 2022). Replacing household fossil fuel combustion with power usage could cause a reduction in air pollution and therefore health risks. Apart from tremendous benefits, decarbonization via electrification of the household energy demand should be based on a holistic low-carbon transition in multiple dimensions. First, the transition in consumer preferences from fossil fuel to electricity plays an important role. Among urban residents, natural gas usage for cooking and space heating could be replaced by electricity usage, accompanied by innovation in electric appliances. Multilevel interventions should be effective enough to change ingrained cooking and heating habits and guide consumer choices towards low-carbon consumption. Second, comprehensive support in the form of infrastructure construction is necessary in the process. To facilitate the large-scale engagement of households and individuals, the upgrading of power grids and building electrical systems is associated with an enormous investment and should be initiated as early as possible. Insufficient charging also hinders residents from transitioning towards electric vehicles. Third, successful electrification should be based on technological innovation to reduce costs. Technologies that should be developed include heat pumps, efficient air conditioners and electric stoves for cooking. In addition, as renewable energy will become the main source of power generation, energy storage technologies should be suitably developed to prevent the unstable energy supply due to seasonal and weather factors and ensure the peak time power usage.

Alternative approaches should be considered to decarbonize household direct energy use, for example, using mini-solar systems for power generation and providing hydrogen for urban cooking and heating. Solar energy exhibits great potential to provide low-carbon energy but is only used for water heating in regard to the household direct energy consumption. Mini-solar power systems can be promoted to overcome storage-related problems and difficulties connecting to power grids. In China, the western provinces are less developed than the eastern provinces but are endowed with abundant solar resources. Additionally, the relatively low population density entails comparative advantages of mini-solar systems for household power generation. With the continuous decrease in the cost of solar technology, it could be feasible to decarbonize the household energy consumption in these regions. In addition, hydrogen could be developed for household direct energy use. Due to the possibility of storage and transportation, hydrogen generated from renewable primary energy sources (solar and wind) could enable the conversion and storage of renewable energy that is sensitive to weather conditions. It could also provide households with energy and thus reduce the difficulty in shifting consumer preferences away from fire-based cooking and heating equipment. To facilitate the innovation and promotion of these technologies, policies, investments and financial support should be guaranteed.

CRediT authorship contribution statement

Xinlu Sun: Formal analysis, Methodology, Writing – original draft. **Zhifu Mi:** Conceptualization, Supervision, Writing – review & editing. **Jin Zhang:** Writing – review & editing. **Jinkai Li:** Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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