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Household fuel and direct carbon emission disparity in rural China

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ABSTRACT

Universal access to clean fuels in household use is one explicit indicator of sustainable development while currently still billions of people rely on solid fuels for daily cooking. Despite of the recognized clean transition trend in general, disparities in household energy mix in different activities (e.g. cooking and heating) and historical trends remain to be elucidated. In this study, we revealed the historical changing trend of the disparity in household cooking and heating activities and associated carbon emissions in rural China. The study found that the poor had higher total direct energy consumption but used less modern energy, especially in cooking activities, in which the poor consumed 60 % more energy than the rich. The disparity in modern household energy use decreased over time, but conversely the disparity in total residential energy consumption increased due to the different energy elasticities as income increases. Though per-capita household CO_2 and Black Carbon (BC) emissions were decreasing under switching to modern energies, the disparity in household CO_2 and BC deepened over time, and the low-income groups emitted ~ 10 kg CO_2 more compared to the high-income population. Relying solely on spontaneous clean cooking transition had limited impacts in reducing disparities in household energy and carbon emissions, whereas improving access to modern energy had substantial potential to reduce energy consumption and carbon emissions and its disparity. Differentiated energy-related policies to promote high-efficiency modern heating energies affordable for the low-income population should be developed to reduce the disparity, and consequently benefit human health and climate change equally.

1. Introduction

Since the reform and opening up in 1978, China's urbanization rate has gradually increased to about 64.7 % by 2021, and the annual income of the rural population increased substantially from < 1,000 CNY per capita to ~ 18,900 CNY, showing a significant rural affluence. The country has completely eliminated absolute poverty in 2021, achieving the Sustainable Development Goal (SDG) 1 - No poverty. But meanwhile, there are a large population, mostly in rural areas, rely on dirty coal and biomass fuels for daily cooking and/or heating, despite of an obvious transition to modern household energies, such as electricity and gas, in the past several decades (Shen et al., 2022a; Tao et al., 2018; Yao et al., 2012). The country still has challenges or even major challenges in the sustainable development, including Sustainable Development Goal (SDG) 7: affordable clean energy (Sachs, et al., 2022; Sustainable Development Report, 2022).

Household energy is a fundamental part of energy consumption in support of life and societal development, with the utilization in cooking and heating activities contributing nearly 80 % of the total household energy consumption (Zheng et al., 2014), but this contributes significantly to air quality and subsequent impacts on human health and climate change (Memmott et al., 2021; Shen et al., 2019; Tao et al., 2021; Yun et al., 2020). Impacts air pollution-associated premature deaths of household energy consumption were reported to much larger than the other sectors especially when indoor exposure was accounted (Lelieveld et al., 2015; Rao et al., 2021), and its impacts magnified from

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energy consumption shares to air quality, and finally health outcomes.

Owing to different energy mix and energy efficiency, household energy consumption can vary significant among different regions and population groups (Aristondo and Onaindia, 2018; Fernandez et al., 2005; Nguyen et al., 2019; Rosas-Flores et al., 2010; Zhu et al., 2019). The disparities in energy consumption may further exacerbate inequalities in the consequent energy expenditure, carbon and pollutant emission, and health impacts (Sun et al., 2021; Yu and Stuart, 2016), being a concern on the unsustainability issue (Andrich et al., 2013). Available studies on household energy inequality discussed disparities and causes in one or several aspects of energy consumption, modern energy access; energy expenditure, and carbon emissions (Adua, 2022, Adua et al., 2022; Baltruszewicz et al., 2021a; Baltruszewicz et al., 2021b; de Almeida et al., 2022; Long et al., 2022; Lyra et al., 2022; Roy and Acharya, 2023; Zhou et al., 2022). In most available studies from developing countries like Zambia (Baltruszewicz et al., 2021b), Vietnam (Nguyen et al., 2019), and India (Fernandez et al., 2005; Roy and Acharya, 2023), it is often concerned on disparities in reliance on traditional solid fuels and/or access to modern clean energies such as gas and electricity. While solid fuel use is not the most critical issue in most developed countries, studies from developed countries like U.S. and Japan evaluated disproportionalities in energy cost, energy poverty, and consequently carbon emissions (Adua, 2022; Adua et al., 2022). The direction and degree in these equality issues are often largely different among these studies due to a number of socioeconomic, technical and behavioral factors like different energy demands, energy structure, energy supply and utilization efficiency, as well as household characterizes.

China is relation to other countries, as the economy grows the gap in expenditure between developing and developed regions will narrow, but the resulting increase in efficiency will not be enough to curb the gap between residential energy consumption (González-Torres et al., 2022). Wang et al. (2023) demonstrate that inequality exists in both commodity energy expenditure and burden in China. Ma et al. (2021a) explored the disparity of energy consumption in 5 Chinese provinces and demonstrated that inequality in residential energy consumption exists and is stronger for electricity. Based on energy data from 12 Chinese provinces, Wu et al. (2017) confirm that disparities exist in energy consumption and expenditure, and vary significantly across energy types, activities, regions, and climatic zones. Some studies have also explored inequalities in commodity energy consumption and resulting emissions based on energy balance sheets from the Energy Statistics Yearbook of China (Chen et al., 2017; Fan et al., 2020; Luo et al., 2023; Wang and Feng, 2021). In addition, energy disparities contribute to inequalities in $PM_{2.5}$ exposure and household carbon emissions (Luo et al., 2022; Xu et al., 2016).

In general, the available articles confirm that inequality does exist in China in terms of residential energy consumption, but there are still some weaknesses. Studies based on input–output tables or data on energy expenditure covered only information on commodity energy such as electricity, gas and coal, but ignored important non-commercial energies like biomass fuels in rural areas. On the other hand, although some articles include information on biomass fuels in their actual surveys, they cover only a part of China due to the difficulty and funding of the survey, and there are significant differences in energy consumption inequality between regions. Due to the limitations of these two factors, existing studies cannot reflect the inequality of all regions and all energy types in rural China, and by comparing existing studies, it is found that the energy inequality changes from year to year as the income rises and the living standard improves. Thus, there is a knowledge gap about the disparity of overall energy consumption in rural China and its trends over time.

In this study, based on a reconstructed household energy database developed from national statistics and recent nationwide field surveys, we evaluated disparities in energy for cooking and space heating among the rural Chinese, decomposed the disparity into different activities, and for the first time revealed the historical changing trend in the household energy disparity since the 1980 s. The Gini coefficient and Concentration Index were calculated to quantitatively assess the energy disparity among people of different incomes. The method and results can shed light on changes in residential energy and its variability as Chinese residents become more affluent, provide a reference for policy makers, and be instructive for other developing countries.

2. Methods

2.1. Residential energy consumption

The residential energy consumption database is a part of the PKU-FUEL database (https://inventory.pku.edu.cn/), which was developed by a research team focusing on energy consumption and major air pollutant emissions at global, regional, and country levels. There is detailed sectorial information with high spatiotemporal resolutions (Wang et al., 2013). Specifically, for the residential energy consumption for cooking and heating in this study, data are from first-hand data obtained from the questionnaire survey in rural China, and estimation models for residential energy consumption (Chen et al., 2016a, Chen et al., 2016b).

The survey was based on energy consumption in 2012, and recalled the activities from 5 (2007), 10 (2002) and 20 years previously (1992). Details of the survey can be found in Tao et al. (2018). Briefly, the questionnaire survey used stratified sampling and a systematic random sampling approach, covering all 31 provinces in China's mainland (except Hong Kong, Macau and Taiwan), and 346 out of all 350 municipalities at the municipal level, with only 4 remote municipalities with less than 0.1 % of households were not included. In total, 34,489 valid questionnaires were identified for data analysis. Besides, daily consumption quantities of biomass fuels and coal with distinct cooking and heating uses was weighed on site for 1670 households. The survey, by introducing time-sharing fractions of different energy types used in different activities, obtained detailed realistic rural household energy consumption data, especially those non-commercial ones and stacked energies in use. The questionnaires covered 2 main direct household energy-consuming activities: cooking and space heating, where cooking activities consisted of 3 components: staple food (grains) cooking, subsidiary food (vegetables and meat dishes) preparation and water boiling, and were accounted according to weights of 25 %, 70 % and 5 % for the time-sharing of cooking energy. On this basis, the data on the energy consumption in different regions were obtained by combining the time-sharing fractions of different energy types and activities in the questionnaire and the solid fuel consumption data obtained at the weighing stage. In terms of specific energy types, including coal, honeycomb briquettes, charcoal, fuelwood, brushwood, straw, corncobs, LPG, biogas, and electricity. The electricity included only the consumption of rice cookers, induction cookers and electric stoves, and other household appliances such as air conditioners and TVs are not covered in the present analysis, as they do not reflect basic needs in daily lives. Both the survey and the data processing process are subject to strict quality control. In addition, the cooking activities in this paper include only the energy consumed directly in the home. Indirect energy consumption activities such as eating out and buying prepared food are not included because the emissions generated do not occur directly in the home.

The residential energy consumption estimation models were regression models based on field-acquired data, using a range of temperature-related variables and socioeconomic parameters, and simulating temporal trends in residential fuels and electricity consumption over seasons and years using a space-for-time substitution approach (Chen et al., 2016a). In this way, energy consumption data were extrapolated to the 1980–2014 interval. This database is believed to be one representative, comprehensive, credible, and systematic database characterizing the realistic situation of household energy consumption in rural China.

2.2. Household carbon emissions

To evaluate changes and disparities in climate impacts associated with household emissions, emissions of CO_2 and several non-CO_2 climate forcers including, CH_4, and N_2O, and an important short-lived climate forcer, Black Carbon (BC), from the burnings of household energies during the activities of cooking and heating were estimated. The emission factors of CO_2 and BC are compiled from published data in literature and can be found in PKU-FUEL database (https://inventory.pku.edu.cn/) in details. Giving limited experimental data on combustion source emission factors of CH_4 and N_2O, values suggested by the Intergovernmental Panel on Climate Change (IPCC) were adopted (Intergovernmental Panel on Climate Change, 2006). Global Warming Potential (***GWP***) is a measure of the magnitude of the impact of different climate forcers on global warming. The IPCC suggested ***GWP*** values of major greenhouse gases in its 3rd Assessment Report, of which $\boldsymbol{GWP}_{CH4,100}$ is ~ 25, meaning that 1 kg CH_4 produces as much radiative forcing effect as 25 kg CO_2, and $\boldsymbol{GWP}_{N20,100}$ is ~ 296. Atmospheric black carbon (BC) has a strong absorption effect on solar radiation contributing strongly to climate change (Jacobson, 2001; Liu et al., 2021), and in the present estimate an average $\boldsymbol{GWP}_{BC,\ 100}$ of 680 was used (Bond and Sun, 2005). Note that uncertainties in the emission and GWP values contributed to the accuracy of the estimated quantitative results, but the disparity and change trends in the household carbon emission are reliable.

2.3. Gini coefficient and concentration index

To quantitatively characterize the disparity of energy consumption among the rural population, we calculated the Lorenz curve and Gini coefficient, which have been widely used in many inequality studies. Following the typical approach (Jacobson et al., 2005), the abscissa of the Lorenz curve represents the cumulative proportion of the population sorted by the consumed energy amount, and the ordinate represents the cumulative proportion of energy consumed. The Gini coefficient quantifies the degree of inequality reflected in the Lorenz curve. Its value range is 0 to 1, and the closer the value is to 1, the stronger the disparities. The Gini coefficient can be defined as follows, where *X* is the cumulative proportion of the population and Y is the cumulative proportion of energy consumption. *X* is measured as the number of energy users in population group i divided by total population, with *X*i indexed in non-decreasing order. *Y* is measured as the quantity of energy used by population group i divided by total energy use, with *Y*i ordered from lowest to highest energy consumption.

$$\boldsymbol{Gini} = 1 - |\sum_{I=1}^{N}(X_{i+1} - X_i)(Y_{i+1} - Y_i)| \tag{1}$$

To evaluate disparity in consumed energy amounts among the population of different income levels, the Concentration index (***CI***), a standard measure initially used to quantify income-related inequalities in exposure, health outcomes and health economics, was adopted and calculated using the method recommended by O'Donnell et al. (2008). ***CI*** was derived as follows, where e_i is the energy amount, μ is the mean of energy amount, and $r_i = i/N$ is the fractional rank of individual i in the per capita income (weighted by county population), with i = 1 for the lowest and i = N for the highest.

$$\boldsymbol{CI} = \frac{2}{N\mu}\sum_{i=1}^{n} e_i r_i - 1 - \frac{1}{N} \tag{2}$$

2.4. Relative variation index and energy elasticity index

The coefficient of variation is a relative statistical measure of the degree of variation in data, which can measure the degree of disparity in the level of economic and social development of a region and its trends, and it plays an important role in analyzing the differences and heterogeneity of observations (Statistical knowledge base, 2023). The relative disparity of residential energy consumption was analyzed using the relative variation index (***RVI***). The calculation formula is as follows, where Q_1, Q_2, and Q_3 are the 25th percentile, median and 75th percentile of energy consumption, respectively. An ***RVI*** value of 0 indicates that the 75th percentile and the 25th percentile are the same and energy consumption is relatively equal, the larger the ***RVI*** value the stronger the relative inequity.

$$RVI = \frac{Q_3 - Q_1}{Q_2} \times 100\% \tag{3}$$

Economic growth requires energy consumption, and there is a certain functional relationship between energy consumption and economic growth. The elasticity coefficient of energy consumption is commonly used internationally to quantitatively examine the relationship between energy consumption and economic growth, and it is also an indicator used in China's statistical yearbook to reflect the proportionality between the growth rate of energy consumption and the growth rate of the national economy (Statistical knowledge base, 2023). Energy elasticity index (***EEI***) is the ratio between the average growth rate of energy consumption ($\boldsymbol{V}_E$) and the average growth rate of income ($\boldsymbol{V}_I$) over the 34-year period from 1980 to 2014. The calculation formula is as follows, where $\boldsymbol{E}_i$ and $\boldsymbol{I}_i$ are the per capita energy consumption and per capita income in year i.

$$\mathrm{EEI} = \frac{V_E}{V_I} \tag{4}$$

$$V_E = \frac{1}{34} \times \sum_{i=0}^{34} \frac{E_{i+1} - E_i}{E_i} \tag{5}$$

$$V_I = \frac{1}{34} \times \sum_{i=0}^{34} \frac{I_{i+1} - I_i}{I_i} \tag{6}$$

2.5. Shapley approach

According to Shorrocks (2013), we decompose the total Gini coefficient into the contributions of different components using the Shapley approach. There is set N has n players k, s of k can be combined into a subset S of N, v (S) is the worth of the coalitions, and mv (S, k) is the marginal contribution generated after k joins the subset S. We used this method to calculate the contribution of cooking and heating to Gini coefficient of residential energy, and further calculated the contribution of residential solid energy and modern energy.

$$e_k = \sum_{S \subset N\ s \in \{0, n-1\}} \frac{s!(n-s-1)!}{n!} mv(S, k) \tag{7}$$

$$\mathrm{mv(S,k) = (v(s \sqcup \{k\}) - v(S))} \tag{8}$$

2.6. Data statistical analysis

Multiple stepwise regression analysis is used to explore the influence of various factors on energy consumption at the municipal level (346 cities). This method has a reasonable independent variable screening mechanism and can avoid the influence of non-statistically significant independent variables on the regression equation. By reviewing the results of relevant literature (Han et al., 2018; Liu et al., 2022; Ma et al., 2021b; Meng et al., 2019; Shen et al., 2022a; Shen et al., 2015; Tao et al., 2018; Wang et al., 2017), we found that the factors affecting residential energy consumption are many and complex, and that the factors and the degree of influence vary across time, regions and interviewed groups. Basically, the factors that are generally considered to have a significant influence on residential energy consumption include: natural factors such as regional geographic environmental conditions and energy endowment; household factors such as household assets and family members' situations; and external factors such as energy infrastructure, government funding and policies. Limited by the accessibility of data, and considering that our aim is not to screen and identify all influencing factors, but to focus on the extent to which certain factors explain energy consumption, the independent variables we selected include: per-person income ($\boldsymbol{I}_{cap}$), total energy production ($\boldsymbol{P}_t$), coal production ($\boldsymbol{P}_c$), electricity production ($\boldsymbol{P}_e$), forest area ($\boldsymbol{F}_{cap}$), arable land area, grain consumption, products of meat consumption, total food consumption (including grain, products of meat, poultry, aquatic products, eggs, milk and dairy products, vegetable and mushroom), regional heating degree days (HDD). This paper uses the 2014 data for regression analysis. For specific results, see **Table s1**.

HDD data were calculated from the recorded ambient temperatures using the method described by Chen et al. (2016a), other data such as coal production, electricity production, arable land area, forest land area, food consumption, etc., were all from the China Statistical Yearbook database (China Statistical Yearbook database, 2022). The five income groups were divided according to the per capita income level of each city on the principle of quintiles. The municipal-level rural residents' income data in the China statistical yearbooks are not available due to incomplete coverage of cities and years. We used the per capita Gross Domestic Product (GDP) data to represent the people's income level in dividing the population into different sub-groups, which is significantly positively correlated with income data ($r = 0.70$–0.75, $p < 0.01$). Data statistical analysis was conducted using IBM SPSS Statistics 20, and non-parameter methods were used. We used Origin 2020b for drawing.

3. Results and discussion

3.1. Historical changes of household energy disparities

In 1980, the national average consumption of residential energy for cooking and heating (***RE***) was 13.6 (11.2–16.9 as IQR) GJ/capita (Fig. 1**a**), and it increased to approximately 14.9 (12.7–18.2) GJ/capita in the early 1990 s. Before the 2000 s, China's rural areas were rarely supplied with commercial energies (Andrich et al., 2013), and the use of modern energy carriers such as gas and electricity for cooking or heating was rare. In the new century, the per capita income of the rural Chinese had surpassed the international poverty line ($1.90/day, about 2,300 CNY/year, purchasing power parity 2011) (World Bank, 2015), and moreover, the supply of rural modern energy has gradually increased , with the proportion of residential modern energy (***RME***) exceeded 1 %, on the national average, and grew rapidly over time. By 2014, the consumption of ***RME*** including gas (LPG and biogas) and electricity increased to 0.5 (0.4–0.7) GJ/capita, reaching 6.6 % (3.7 %-11.4 %) of the total ***RE***. With the increased utilization of modern energies and the optimization of energy equipment that improved energy conversion efficiency, the total ***RE*** consumption declined obviously. It dropped to 8.2 (5.3–11.5) GJ/capita in 2014, which was nearly half of that in the early 1990 s. Historical changes in the ***RME*** and the ***RE*** generally showed an opposite trend, with a significant negative correlation (***r*** =

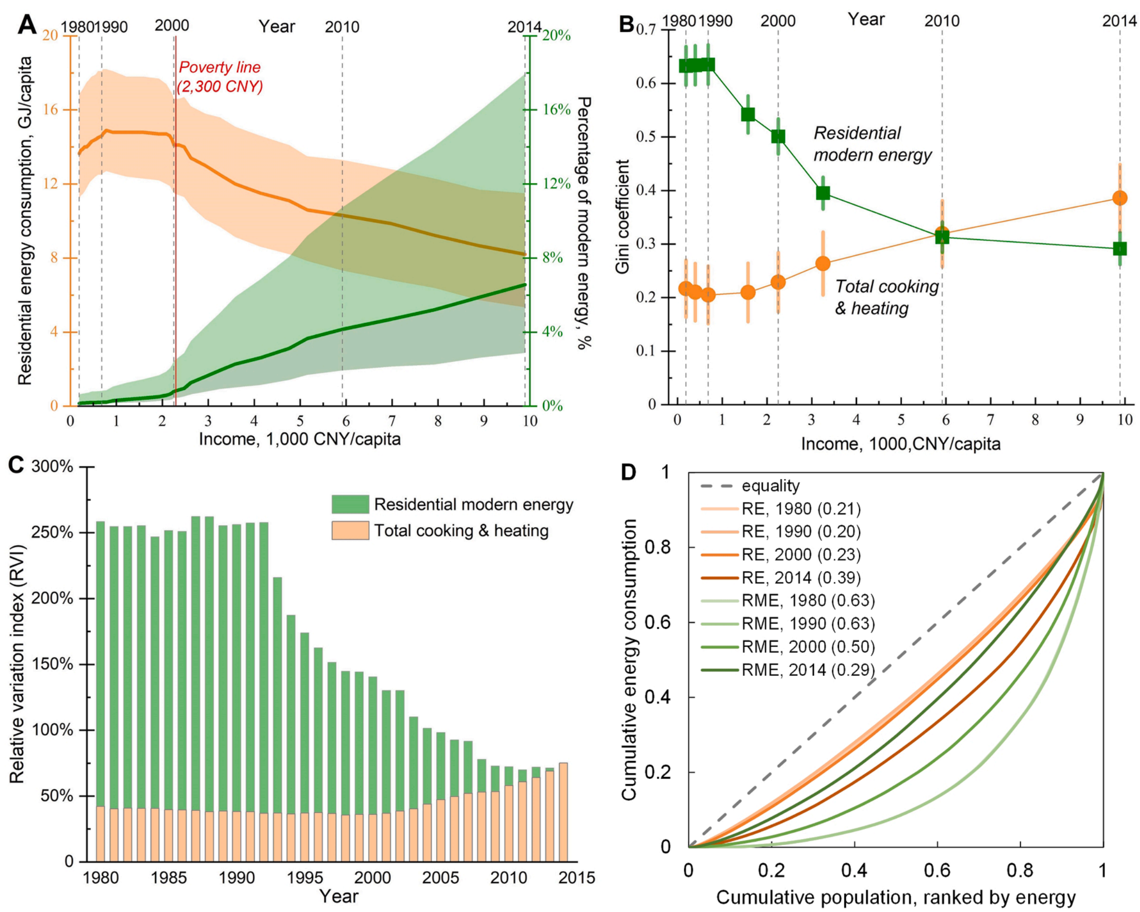

Fig. 1. Energy consumption, Gini coefficient and Relatively variation index. A, consumption amounts of the residential energy for cooking and heating (***RE***) and the modern energy (***RME***) of rural Chinese. **B**, Gini coefficients of ***RE*** and ***RME***. **C**, relatively variation index (***RVI***) of ***RE*** and ***RME***. **D**, the Lorenz curves of ***RE*** and ***RME*** of rural Chinese in 1980, 1990, 2000 and 2014. Data are the national average in China but those in Hong Kong, Macao, and Taiwan are temporally not available in this study.

-0.683, $p < 0.01$). By 2014, 22.7 % (140 million) of the rural Chinese were able to meet their daily cooking/heating needs by using less than 5 GJ (energy absolute poverty line 2021) (Poblete-Cazenave et al., 2021) of energy, implying relatively high energy efficiency rather than energy poverty. In contrast, 33.2 % (205 million) used more than 10 GJ, indicating a certain degree of inequality in energy consumption.

Although the average income in rural China has exceeded the poverty line since 2000s, 9 % of the population was still in income poverty in 2014 (Luo et al., 2020). As the most basic activity in the daily life, the energy consumption for cooking and heating also existed high variabilities. The absolute disparity of energy consumption was expressed by the Gini coefficient, and the relative disparity was studied by examining the Relative Variation Index (***RVI***) here. The energy disparity is displayed numerically in Fig. 1**B** and Fig. 1**C,** which plot the Gini coefficient of ***RE*** (G_{RE}) and ***RME*** (G_{RME}), and the ***RVI*** of ***RE*** (V_{RE}) and ***RME*** (V_{RME}). As seen, there are always disparity concerns, and in most of the time, the disparity in ***RME*** was much stronger than that in ***RE***. The absolute disparity in ***RME*** decreased significantly with increase access and utilization of modern energy in the rural communities, with the G_{RME} decrease from 0.63 (0.60, 0.67 as 95 %CI) in 1980 to 0.29 (0.26, 0.32) in 2014. However, the disparity of the total ***RE*** gradually deepened due to distinct rates in elimination of traditional solid fuels and varied adoption of modern energies. The G_{RE} increased gradually from 0.21 (0.16, 0.27) in 1980 to 0.39 (0.32, 0.45) in 2014. This can also be seen in the historical trend of the Lorenz curves, where the Lorenz curves of ***RE*** gradually moved away from the line of absolute equality, while ***RME*** showed the opposite trend (Fig. 1**D**). A similar trend was observed in the relative disparity, with the V_{RE} increasing from 42.3 % to 75.1 % but the V_{RME} declining from 258.4 % to 71.9 %. This was associated with changes in distinct patterns in cooking/heating energy structures and temporal characteristics, the details of which are discussed in the next section.

3.2. Energy disparities in cooking and heating activities

Cooking and space heating are basic demands in the human life. The consumption amount of residential energy for cooking (RE_C) was much higher than that for heating (RE_H). Historical change trends suggested that when the rural population became rich, their consumption of energy for cooking decreased gradually, from 10.4 (9.1–11.5) GJ/capita, on the national average, in 1980, to 5.1 (3.7–6.6) GJ/capita (by approximately 50 %) in 2014 (Fig. 2**A**). But, the consumed energy for space heating changed small, and was 2.3 (0.9–5.9) GJ/capita by 2014. There were substantial variations in the changing trends among different regions, especially for the cooking energy, that would be discussed in detail in the next section. The RE_C showed a significant negative correlation with residential modern energy for cooking (RME_C) ($r = -0.847$, $p < 0.01$), but there was no significant correlation between RE_H and residential modern energy for heating (RME_H). The reduction in the household energy consumption per capita was believed to be closely associated with increased energy utilization efficiencies, for example, by using energy-saving cookstoves, and more important,

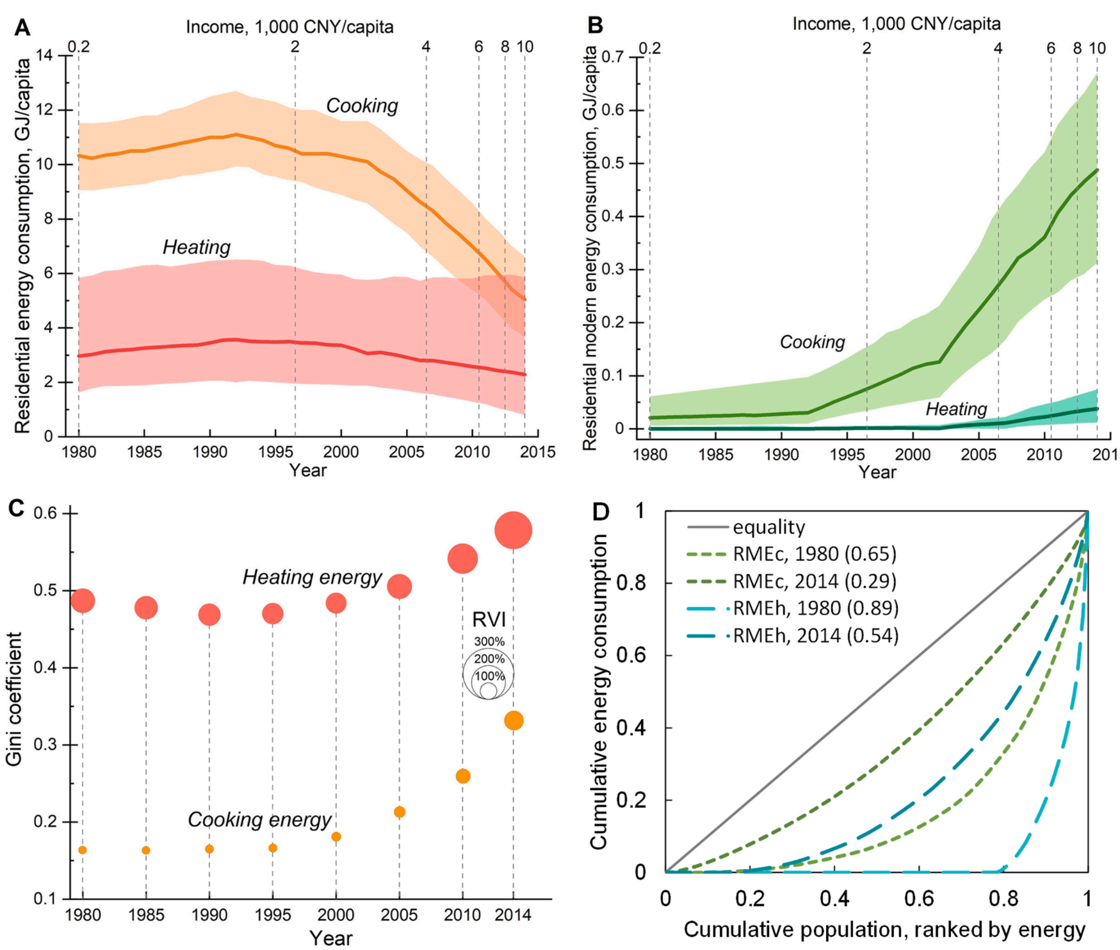

Fig. 2. Energy consumption, Gini coefficient and Relatively variation index by cooking and heating. A and B, the consumption amounts of energy (***RE***) and the modern energy (***RME***) for cooking and heating separately in rural households. **C**, the Gini coefficients and the Relative Variation Index (***RVI***) in the ***RE*** for cooking and heating. **D**, the Lorenz curves and Gini coefficient of ***RME*** for cooking and heating. Data are the national average in rural China but those in Hong Kong, Macao, and Taiwan are temporally not available in this study.

significant adoption of modern energies. The consumption amount of $\boldsymbol{RME}_{\mathrm{C}}$ increased to 0.5 (0.3–0.7) GJ/capita in 2014 (Fig. 2**B**), comprising to about 10 % of the $\boldsymbol{RE}_{\mathrm{C}}$. Compared to clean cooking, clean heating is much more challenged, especially in scattered rural areas (Shen et al., 2022a; Shen et al., 2022b; Tao et al., 2018). By 2014, on the national scale, the relative shares of $\boldsymbol{RME}_{\mathrm{H}}$ in $\boldsymbol{RE}_{\mathrm{H}}$ was only 1.7 %, but this fraction varied largely among different households.

In 2014, one-fourth (162 million) of people consumed < 1 GJ/capita for space heating, but approximately 11 % (68 million) needed > 10 GJ/capita to ensure thermal comfort in their homes, and mainly relied on traditional dirty solid fuels. The disparities in the $\boldsymbol{RE}_{\mathrm{H}}$ were associated with regional meteorological conditions and resource availability. The results of multiple stepwise regression analysis showed that heating degree days (HDD) was significantly affected the $\boldsymbol{RE}_{\mathrm{H}}$ ($p < 0.05$), accounting for nearly 85.3 % of the $\boldsymbol{RE}_{\mathrm{H}}$ variation among different households (**Table s1**). Energy consumption was also closely associated with the energy structure, in which resource availability and affordability were critical influencing factors. The influences of these factors were also significant as seen from the regression model. However, there is no significant correlation between HDD and $\boldsymbol{RE}_{\mathrm{H}}$ in terms of interannual variation. For the cooking energy consumption, per capita coal production, income and HDD can only explain 63.4 % of its variation (**Table s1**), and factors such as energy efficiency and dietary habits may also have an impact (Hou et al., 2017), but pursuing no hunger is the most important and basic demand. The per-capita consumption varied much smaller compared to the $\boldsymbol{RE}_{\mathrm{H}}$, and the $\boldsymbol{RVI}$ values in the $\boldsymbol{RE}_{\mathrm{C}}$ and $\boldsymbol{RE}_{\mathrm{H}}$ were 58 % and 219 %, respectively. Consequently, the disparity in the $\boldsymbol{RE}_{\mathrm{C}}$ was much smaller compared to that in the $\boldsymbol{RE}_{\mathrm{H}}$.

Although the $\boldsymbol{RE}_{\mathrm{H}}$ was much less than the $\boldsymbol{RE}_{\mathrm{C}}$, it was found that the disparity in the former was obviously stronger than that in the latter. The Gini coefficient for the $\boldsymbol{RE}_{\mathrm{H}}$ in 1980 was 0.49 (0.43, 0.54), which was significantly higher than that of 0.16 (0.12, 0.21) for the cooking energy (Fig. 2**C**). Historically, in the context of the decline in both $\boldsymbol{RE}_{\mathrm{H}}$ and $\boldsymbol{RE}_{\mathrm{C}}$, the disparity of them both increased slightly, as seen from increased Gini coefficients (Fig. 2**C**). The relative disparities also increased over time (Fig. 2**C**). It is further noted that, the consumption of modern energy carriers for space heating ($\boldsymbol{RME}_{\mathrm{H}}$) was much more variable, with a Gini coefficient of 0.89 (0.87, 0.92) in 1980 and 0.54 (0.51, 0.58) in 2014 (Fig. 2**D**), although it was only a small fraction of the $\boldsymbol{RE}_{\mathrm{H}}$.

3.3. Regional differences on income impacts on energy consumption

People living in different regions are expected to have distinct daily activity patterns and different energy demands due to factors such as climatic conditions, regional energy endowment and the completeness of energy infrastructure (Ma et al., 2021b). In this section, we further analyzed inter- and intra-regional disparities in rural households. Most of northern households experienced temperate monsoon and temperate continental climate with cold and dry winters, resulting in higher $\boldsymbol{RE}_{\mathrm{H}}$. For example, along with its high HDDs, the $\boldsymbol{RE}_{\mathrm{H}}$ of people from the Northeast China was as high as 11.9 (10.3–12.9) GJ/capita in 2014, accounting for nearly 70 % of the $\boldsymbol{RE}$, and was nearly 5 times the national average $\boldsymbol{RE}_{\mathrm{H}}$. The South area has a subtropical monsoon climate, which is warm and humid throughout the year, thus, most residents do not need space heating in winter. The observed inter-regional difference was closely related to different HDDs across the regions, being consistent with the significant influence of HDD. Household income difference was another factor influencing the $\boldsymbol{RE}$ in homes from different regions. The results of the multiple stepwise regression model showed that HDD and income together explained 87.0 % of the variation in $\boldsymbol{RE}$ among different households, while income explained 54.6 % of the variation in $\boldsymbol{RME}$ (**Table s1**). In order to investigate whether the extent of the effect of income on $\boldsymbol{RE}$ and $\boldsymbol{RME}$ varies across regions, we used the energy elasticity index to explore the driving effect of interannual changes in income on energy consumption (see **Method**).

We observed that since the 1980, the changing rates of or fluctuation in household energy consumption were much smaller than that of income, with the elasticity index values ranging from −0.35 to 0.03. It was more interesting to find that, the energy elasticity index in the south China, especially those located in the southeast coast, was negative and more elastic compared to that in the north (Fig. 3**a**). The decline in household energy consumption with the income increase was much more significant in the southeast. The energy elasticity index values were relatively small in most northern households, suggesting that the income growth in the north had a smaller driving effect on household energy consumption than that in the south, in other words, the household energy consumption was insensitive to the income change. Moreover, in the Inner Mongolia, Tibet, Gansu and Xinjiang provinces, the energy elasticity index was positive, indicating more energy consumption along with the increased income during the past three decades. The differences in the energy elasticity index further widen the original differences in the $\boldsymbol{RE}$ between regions and increase inter-regional inequality over time (which can be seen in Fig. s1**a** for residential energy consumption by province in 1980 and 2014). Such disparity was closely associated with the utilization of commercial energies. Even though residential energy expenditure has increased due to the rise in commodity energy consumption, it remains a relatively small share of household income at less than 5 % (Han et al., 2018; Nie et al., 2018). In 2014, the people in the East coastal areas consumed 0.8 GJ $\boldsymbol{RME}$ per capita, but those living in the western areas had the lowest $\boldsymbol{RME}$, at only 0.3 GJ/capita. The elasticity index in $\boldsymbol{RME}$ ranged between 0.28 and 1.09 (Fig. s2**a**), indicating more consumption of modern energies under the affluence, but very large inter-region disparities. The modern energy elasticity index appeared to be larger in some central and inland provinces compared to the coastal area. This means people from those central and inland provinces had more utilization of those clean modern energies when being richer, and consequently, the regional disparity of $\boldsymbol{RME}$ gradually decreased over time (which can be seen in Fig. s1**b** for residential modern energy consumption by province in 1980 and 2014).

Even for the people living in the same region with a similar living climate, there were still certain differences in the energy consumption due to factors like income levels, lifestyle habits, family size, awareness of energy saving and education levels of family members (Han et al., 2018). The intra-regional disparities in the $\boldsymbol{RE}$ and the $\boldsymbol{RME}$ are further discussed by calculating the provincial-level Gini coefficients in 2014. Overall, the intra-provincial disparity was smaller compared to the inter-provincial inequality, $\boldsymbol{G}_{\mathrm{RE}}$ in the range of 0.07 to 0.54 for different provinces (Fig. 3**B**), and $\boldsymbol{G}_{\mathrm{RME}}$ ranged from 0.07 to 0.49 (Fig. s2**b**). The $\boldsymbol{G}_{\mathrm{RE}}$ was found to be significantly negatively correlated with the HDD ($\boldsymbol{r} = -0.412$, $p < 0.05$), indicating that in cold regions, the intra-provincial inequality in household energy consumption was small. This could be explained by the fact that in these regions, nearly all residents had to rely on full heating loads to get through the cold winter and mostly consumed traditional coals and biomass fuels, while in the central and southern regions, where wintertime temperatures are relatively high, there are substantial differences in heating demands across the households, depending on the willing, affordability, heating duration and costs, leading to higher differences in their $\boldsymbol{RE}$ consumptions. The provincial $\boldsymbol{G}_{\mathrm{RE}}$ did not correlate with the income levels, but there was a negative correlation between the $\boldsymbol{G}_{\mathrm{RME}}$ and the income ($\boldsymbol{r} = -0.417$, $p < 0.05$), that was the $\boldsymbol{G}_{\mathrm{RME}}$ values were relatively small in provinces with higher income levels. The $\boldsymbol{G}_{\mathrm{RME}}$ was not significantly correlated with the HDD. As HDD reflected local meteorological condition, it is further implied that without effective interventions, residential energy inequality is likely to persist even if people became rich in the future.

3.4. Energy disparities in different income groups

We clearly demonstrated that there were significant disparities in the residential energy consumption among rural Chinese, and that economic status played an important role in the energy consumption inequality. Despite more family incomes since the reform and opening up policy in

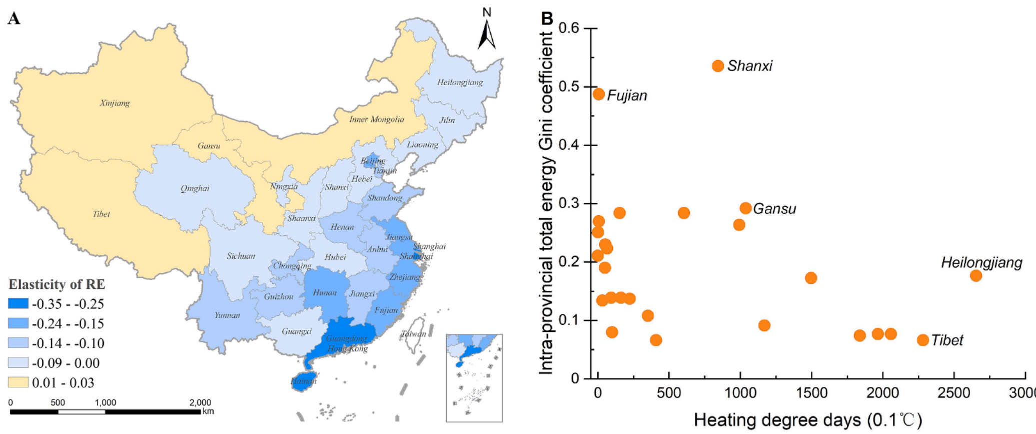

Fig. 3. Provincial energy elasticity index and energy Gini coefficient. A, energy elasticity index of rural residential energy consumption by province in China. **B**, intra-provincial Gini coefficient of residential total energy.

the country, income disparity has always existed. The income Gini coefficient has gone from 0.32 in 1980 to about 0.47 in 2014 and the latest announcement of 0.47 in 2021 (Xie and Zhou, 2014; China Statistical Yearbook database, 2022). Here, we further analyzed disparities in the ***RE*** and ***RME*** among people of different income levels, by using the Concentration Index (***CI***). A negative ***CI*** value indicates more energy consumed by the low-income population, while a positive value indicates that it is concentrated among high-income people. As seen in Fig. 4**A**, the ***CI*** values of the ***RE*** were generally negative, which was close to 0 (0.04, −0.04) in 1980, and decreased gradually to −0.09 (-0.17, −0.01) in 2014. This means that the low-income people consumed more ***RE*** directly in their homes to meet their daily basic needs compared to the high-income group, and this disparity deepened over time. However, for the ***RME***, the rich occupied more than the poor as the ***CI*** values were positive. The ***CI*** value of the ***RME*** generally declined from 0.25 (0.17, 0.34) in 1980 to 0.07 (0.03, 0.11) in 2014, indicating that the degree of disparity in more modern energy consumed by the rich became smaller. This can also be evident by the historical trend of the Concentration curves (Fig. s3**a**), which lied above and gradually moved away from the absolute equality line for ***RE***, while the Concentration curves for ***RME***

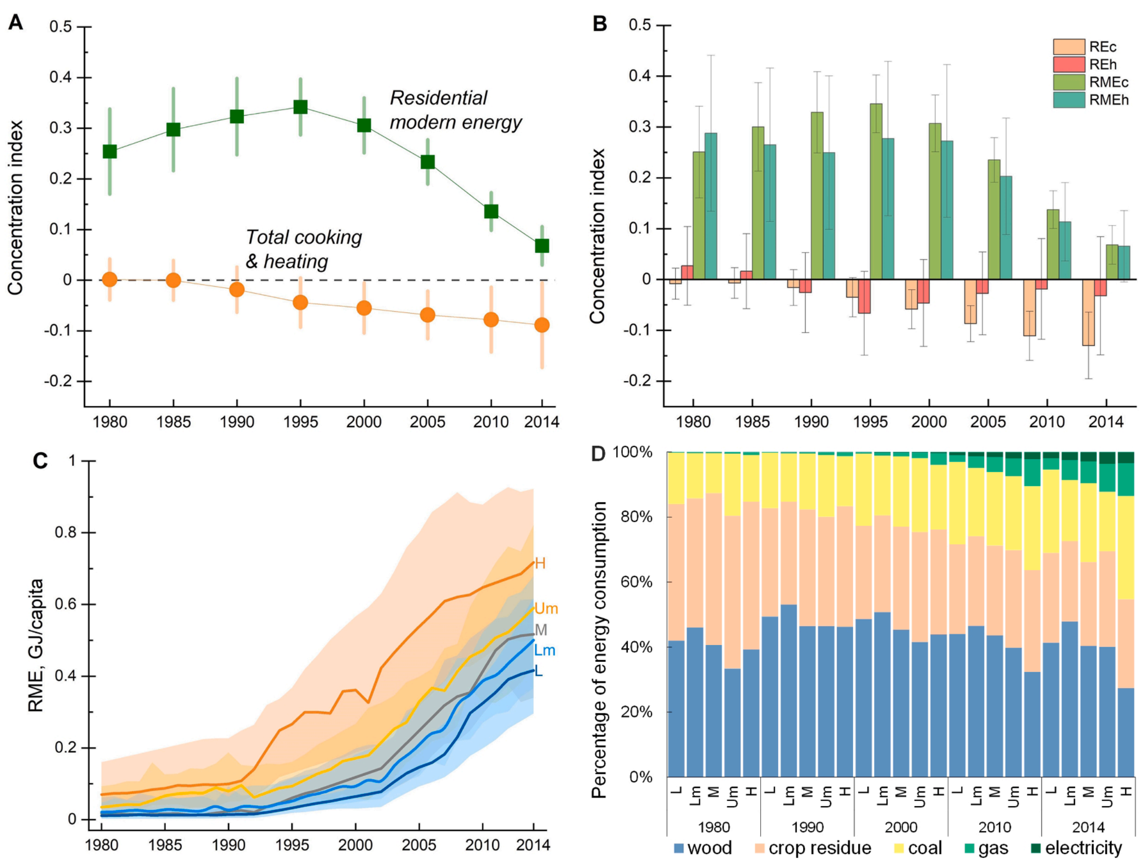

Fig. 4. Energy consumption and Concentration index by income groups. the Concentration index values in the consumption amounts of total residential energy (***RE***) and household modern energy (***RME***) among rural Chinese (**A**), and those for cooking and heating separately (**B**); historical changes in the ***RME*** (**C**) and the structure of cooking energy consumption for the rural people of different incomes (**D**). Data are the national average in rural China but those in Hong Kong, Macao, and Taiwan are temporally not available in this study.

showed an opposite trend. By looking into the cooking and heating activities separately, it was found that, firstly, for both activities, the ***CI*** values of the ***RE*** were negative and those of the ***RME*** were positive (Fig. 4**B**), indicating the poor directly consumed more total cooking/heating energy but less modern cooking/heating energy. Secondly, the disparity degree in the cooking energy between the poor and the rich appeared to be stronger than that in heating energy, as the ***CI*** values of the cooking energy were larger than those of the heating energy, and the arc of the Concentration curves for cooking energy is greater than heating (Fig. s3**b**).

The study population was divided into five income groups: low-income, lower-middle-income, middle-income, upper-middle-income, and high-income. The high-income group had a relatively high ***RE*** at the beginning, but the ***RE*** decreased obviously over time, meanwhile, the poor group although had lower ***RE*** in the 1980 s, the average ***RE*** in 2014 was the highest among the five income groups (Fig. s4**a**). For the cooking energy, the difference in the RE_C among different income groups was small early, but different transition rates led to obvious differences in the 21st century (Fig. s4**b**). The poor had smaller reductions in the RE_C, resulting in more energy consumed for cooking for them. By 2014, the rich could meet their direct cooking needs by using only 3.6 (2.6–6.6) GJ/capita energy consumption, but the poor used 60 % more at 5.9 (5.2–8.6) GJ/capita. In terms of the ***RME***, people with higher income consumed more modern energy, especially after the 1990 s when people had more access and increased utilization of modern energies (Fig. 4**C**). In 2014, the ***RME*** of the high-income group was 0.7 (0.5–0.9) GJ/capita and that of the low-income group was 0.4 (0.3–0.6) GJ/capita, with a difference of about 1.8 times. Modern energies are mostly used for cooking (84–95 %), while space heating only accounted for a small part. The rich had a higher proportion of modern energies used for cooking, at 19.9 % (8.3 %-28.1 %) of the total cooking energy, compared to the poor at 6.1 % (3.1 %-9.7 %) (Fig. 4**D**), highlighting significant inequalities in the utilization of modern energies in different income groups. This also reflects that the poor still rely on traditional inefficient stoves, while the rich use more efficient energy-saving stoves.

3.5. Disparities in household CO_2 and BC emissions

Per-capita household CO_2 emission from direct residential energy consumption of rural Chinese in 2014 was 653 kg, ranging from 373 to 753 kg. The Gini coefficient in per-capita CO_2 emission was 0.35 (0.29–0.41), indicating a significant inequality in the household CO_2 emissions associated with the basic cooking/heating activities. Per-capita CO_2 emission was negatively correlated with income ($p < 0.01$), and the low-income groups emitted ~ 10 kg CO_2 more in terms of direct household energy consumption compared to the high-income population. This is explained by that the low-income population consumed more coals. CO_2 emission was negatively correlated with the proportion of modern energy (r = -0.296, $p < 0.01$), and per-capita CO_2 emission of people from the Northwest China, who had the lowest proportion of modern energy, was as high as 1088 kg, that was nearly 3.8 times higher than that of people in South China (285 kg/capita). Since the 1980, the disparity in household CO_2 emission in rural China deepened, with the Gini coefficient increasing from 0.27 in 1980 to 0.35 in 2014.

Besides CO_2, other greenhouse gases such as CH_4 and N_2O, and carbonaceous particulate matters like BC are also often accounted in many climate impact studies. Residential combustion source is believed to be an important source of BC in many developing countries, and in China it contributed nearly one-third of the national total emission (Xu et al., 2021). The emissions of CH_4 and BC from household energies were 2.5 (1.1–2.9) kg/capita and 1.3 (0.6–1.6) kg/capita in 2014, respectively. While these non-CO_2 compounds were taken into the consideration, the per-capita GWP_{100} value generated by emissions from rural residential energy consumption was 2001 (1500–2190) kg CO_2-equivalent per year in 1980, increased to about 2450 (1760–2680) kg CO_2-equivalent per year in the early 1990 s, and then gradually declined to 1617 (854–1940) kg CO_2-equivalent per year by 2014 (Fig. 5**A**). The GWP_{100} value significantly positively correlated with the ***RE*** (r = 0.986, p < 0.01) and negatively with the fraction of ***RME*** in ***RE*** (r = -319, p < 0.01), implying that the population with higher residential energy amount and a low share of modern energy contributed more to emissions of these warming forcers. The Gini coefficient in GWP_{100} was 0.39 in 2014, larger than the Gini coefficient in household CO_2 emission only (Fig. 5**B**). This indicates that by taking more climate forcers into the consideration especially BC, the disparity in household carbon emissions increased substantially. This is mainly because the disparities in BC and CH_4 emissions were stronger than that of CO_2, and the Gini coefficient of BC in 2014 is 0.43 (0.38–0.50). The poor population with higher consumptions of traditional solid fuels had higher GWP_{100} values. The disparity in household GWP_{100} also deepened over time, from 0.23 (0.17–0.28) in 1980 to 0.39 (0.33–0.49) in 2014 (Fig. 5**C**), which suggested that under the clean household energy transition in rural China, although the absolute amount of carbon emission reduced, the disparity was increased substantially, and while non-CO_2 compounds were considered, the deepened inequality issue in climate impacts of household emissions would be more serious.

4. Discussion and implications

Household energy inequality is closely related to many issues like energy security, energy poverty, air pollution exposure and sustainable development. While the country successfully achieved the SDG 1 no poverty, it remains significant challenges in SDG 7 as still many people use dirty solid fuels in their daily lives. This consequently affect the achievement of other SDGs such as the human health and inequality. Household energy consumption disparity and its historical trend under the fast socioeconomical development and the affluence had not well understood yet. This study assessed disparities and the changing trends in rural household energy consumption by activity type, spatial location and income group, in conjunction with cooking and space heating energy consumption, and the resulting disparities in carbon emissions. It for the first time revealed the historical changing trend in the household energy consumption disparity in rural China, which including both commodity and biomass energy and covered all provinces in the mainland.

The Gini coefficient for the national total residential energy was 0.39 in 2014, indicating serious inequalities in household energy consumption in the country. One previous study on rural household energy from 12 provinces in China reported a Gini coefficient of 0.41 in 2013 (Wu et al., 2017), and another study of 5 provinces reported a Gini coefficient of 0.30 in 2018 (Ma et al., 2021a). Both studies indicated significant inequalities in the residential energy consumption in rural China, although these two previous studies were only from a few provinces. Compared to the residential energy inequality issue in other developing countries, such as Vietnam (0.35 in 2014), Kenya (0.87 in 2000), Thailand (0.61 in 2000), and El Salvador (0.60 in 2001) (Jacobson et al., 2005; Nguyen et al., 2019), the inequality in rural China appeared to be smaller. We demonstrated that the disparity in direct residential energy consumed for space heating was stronger than that for cooking, and the former disparity was more prominent in spatial disparities. The results of the Shapley approach (see **Method**) confirmed that the direct residential energy consumption disparity was mainly in the energy consumption for heating (82 % of the total), and modern energy contributed (38 % and 46 % of the cooking and heating energy disparity, respectively) less than the solid fuels. The energy disparity was stronger in those with lower heating demand (less consumption for space heating), and modern energy inequality was more prominent in the population with lower incomes.

We analyzed the differences in energy consumption among different income groups by calculating the Concentration Index of residential energy consumption. The negative ***CI*** value declined and was −0.09 in

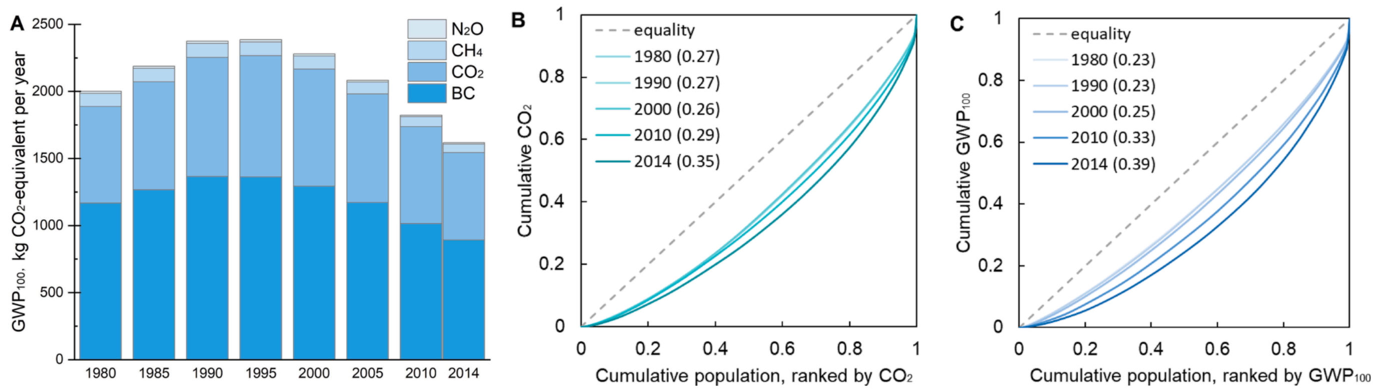

Fig. 5. ***GWP_{100}* and Lorenz curves of *CO_2 and GWP_{100}*.** A, the ***GWP_{100}*** of N_2O, CH_4, CO_2 and BC. B, the Lorenz curves of ***CO_2*** in different years, the numbers in parentheses are the Gini coefficients. C, the Lorenz curves of ***GWP_{100}*** in different years.

2014, but meanwhile, the ***CI*** values of the ***RME*** were positive and became smaller over time. This suggested that the poorer people used more total but less modern energy directly in household cooking and heating activities. The disparity degree in the cooking energy among different income groups was stronger than that in the heating energy, as the ***CI*** values were larger. The poor consumed more traditional energies as they still highly relied on low-efficient energy stoves and polluting fuels like coal and raw biomass fuels for daily cooking and heating. This resulted in more greenhouse gases emissions of the poor compared to the rich. The low-income groups emitted ~ 10 kg more CO_2 per capita in terms of direct household energy consumption compared to the high-income population. The disparity in household carbon emission deepened over time. Wang and Feng (2021) have demonstrated that the inequality in CO_2 emitted by residential commodity energies consumption also deepened over time. By adopting modern energies, the rich not only consumed less energies for cooking and/or heating but also inhaled cleaner air.

Due to the difficulty, high cost and long period of a large-scale national energy survey, the study in this paper only goes up to 2014. Influenced by the socioeconomic development and the gradual affluence of the people, household energy consumption is still undergoing transformation and change, and it is necessary to continue to invest more in conducting newer national surveys and studies. Even so, some patterns can be identified by analyzing the key drivers behind changes in disparities. At the macro level, disparities in energy consumption may be influenced by a variety of factors such as regional climatic conditions, energy endowment, income, energy infrastructure, energy supply, and energy-related policies. Provided that the first two geographic conditions are relatively stable, the remaining factors are likely to be the main causes of variation in energy disparities. The results of the multiple regression show that per capita income, total energy production and electricity production combine to explain 94.8 % of the variation in $\boldsymbol{G}_{\mathrm{RE}}$ and 98.0 % of the variation in $\boldsymbol{G}_{\mathrm{RME}}$ (**Table s1**), and that income is significantly correlated with both $\boldsymbol{G}_{\mathrm{RE}}$ ($\boldsymbol{r} = 0.924$, $p < 0.01$) and $\boldsymbol{G}_{\mathrm{RME}}$ ($\boldsymbol{r} = -0.959$, $p < 0.01$).

In terms of time, it can be roughly categorized into three phases based on how the factors have changed (see China's main rural energy policies since 1980 in **Table s2** and the relationship between income and energy Gini coefficients in **Fig. s5**): The first phase is the 1980–2000 (past), a period in which per capita income showed steady growth, and energy policy was focused on accelerating the construction of energy infrastructure and steadily upgrading the technology development, due to an incomplete energy infrastructure and a smaller supply of commodity energy, and changes in energy inequality were small; The second phase is 2001–2020 (present), this stage with the rapid development of China's economy, the per capita income shows rapid growth. China's energy policy focused on promoting clean energy and improving air quality, like coal-to-electricity policy and a campaign to replace residential solid fuels with electricity or natural gas in Beijing, Tianjin and the surrounding 26 cities in northern China (Liu et al., 2021; Meng et al., 2019; Zhou et al., 2021). The level of energy infrastructure construction has accelerated, the supply of clean energy has increased, and the energy disparity has changed significantly, with the $\boldsymbol{G}_{\mathrm{RME}}$ declining from 0.50 to 0.29 in 2014, and $\boldsymbol{G}_{\mathrm{RE}}$ increased slightly from 0.23 to 0.39. According to the relationship between income and the Gini coefficient at this stage, it is predicted that by 2020 $\boldsymbol{G}_{\mathrm{RE}}$ will be 0.43 (0.38, 0.47) and $\boldsymbol{G}_{\mathrm{RME}}$ will be 0.18 (0.16, 0.20); The third stage is after 2021 (future), when per capita incomes are likely to continue to rise, energy policies focused on promoting rural energy transformation and accelerating clean and low-carbon energy transition, and clean energy consumption is likely to continue to rise. Therefore, it is expected that the inequality in residential modern energy would decline with more access to affordable modern energies, but the inequality would not be totally eliminated and is likely to persist even under optimistic socioeconomic growth scenarios (Poblete-Cazenave et al., 2021), and universal access may not be achieved even in 2050 (Pachauri et al., 2021). In addition, total energy variability is likely to be greater and calls for more interventions.

Residential solid energy is a major determinant of energy disparity in both heating and cooking activities, so reducing its use and individual differences is a priority for reducing inequality. This can be a challenging and daunting task, but if traditional solid fuels can be used efficiently through modern energy-saving cookstoves and heating facilities, it will also help to reduce inequalities in household emissions. Increasing access to clean cooking and heating energy is important and can help reduce inequality by increasing subsidies and incentive policies for efficient electrical appliances and energy efficient buildings (Bertoldi, 2022). In addition, increased use of clean energy will further drive down consumption of solid fuels, especially biomass, thereby reducing indoor and outdoor air pollution and its impact on human health, and these policy interventions will also help reduce future health costs (Bertoldi et al., 2021). The rapid residential energy transition benefits more in the middle- and high-income population but less for the low-income people (Barrington-Leigh et al., 2019). To reduce residential energy disparity, more attention needs to be paid to the poor in the formulation of energy transition-related policies, with flexible targets and appropriate subsidies to help them overcome the difficulties and challenges. Actions of clean heating and cooking energy intervention should have different objectives and pathways. Heating is more variable and the transition to clean energy is more difficult, so differentiated policies and supports should be developed for the specific circumstances of the region, and the requirements should be appropriately relaxed for places with high heating demand. With those efforts, it is expected to have synergetic effects in multiple SDGs, at least coordinated SDG 3, 7, and 10.

CRediT authorship contribution statement

Ran Xing: Writing – original draft. **Zhihan Luo:** Methodology. **Wenxiao Zhang:** Data curation. **Rui Xiong:** Methodology. **Ke Jiang:** Software. **Wenjun Meng:** Data curation. **Jing Meng:** Supervision. **Hancheng Dai:** Supervision. **Bing Xue:** Supervision. **Huizhong Shen:** Supervision. **Guofeng Shen:** Writing – review & editing, Supervision, Funding acquisition.

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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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2024.108549.

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