Journal of Cleaner Production 450 (2024) 141871

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Rural household energy transition in China: Trends and challenges

Xiang Zhang [a,*], Christopher P. Barrington-Leigh [b,c], Brian E. Robinson [a]

[a] Department of Geography, McGill University, Montreal, Quebec, Canada
[b] Department of Equity, Ethics, and Policy, McGill University, Montreal, Quebec, Canada
[c] Bieler School of Environment, McGill University, Montreal, Quebec, Canada

ARTICLE INFO

Handling Editor: Giovanni Baiocchi

Keywords:
Household energy
Energy transition
Temporal trends
Rural China

ABSTRACT

Against the backdrop of both environmental and health issues caused by inefficient combustion of solid fuels in households, the transition to clean energy is a critical development imperative. This study uses publicly available administrative data spanning nearly 30 years at the provincial level to characterize the "business as usual" (BAU) energy transition in China's rural household sector in order to inform interventions needed to achieve clean energy goals. We first describe the temporal trends and spatial characteristics of energy transitions over the past three decades. We then use a simple two-way fixed effects model to estimate the role that household income growth plays in this transition process. Finally, we predict the timeline for the BAU rural energy transition with an autoregressive integrated moving average (ARIMA) model. Our results show that China's rural household sector has gradually undergone a consistent but geographically uneven transition over the past three decades. Compared with warmer provinces without indoor heating, where a 1000 RMB increase in per capita income is associated with a 5–10% increase in the share of clean energy, in provinces with heating needs the predicted effect is less than 2%. ARIMA model projections suggest that without policy interventions, for most provinces in northern China the share of clean energy would remain less than 40% by the year 2050. The "clean heating program" implemented in the North China Plain in 2015 has therefore advanced the energy transition by 10 years in just the 3 years between 2015 and 2018. Together, these results show the potential for interventions in helping spur energy transitions.

1. Introduction

Approximately one-third of the world's population relies on solid fuels such as biomass and coal for their basic energy requirements, such as cooking, heating, and lighting (IEA, 2022). However, the process of burning these fuels contributes significantly to air pollution and health problems, particularly in low- and middle-income countries (Rehfuess and World Health Organization, 2006; Kim et al., 2011; Jeuland et al., 2015). Household air pollution, a consequence of burning solid fuels, has been linked to acute lower respiratory infections in children, chronic obstructive pulmonary disease, and lung cancer in adults (Rehfuess et al., 2017). In 2019, household air pollution caused over 2.3 million premature deaths, with over 95% of these deaths occurring in low to medium Socio-demographic Index countries (Institute for Health Metrics and Evaluation (IHME), 2020). The use of solid fuels also results in time loss for education, rest, and productive activities, particularly for children and women, due to the time spent collecting and preparing biomass fuel (World Health Organization, 2016; Biswas and Das, 2022). Furthermore, energy expenditures often represent a significant portion of low-income households' budgets (Adkins et al., 2012; Sánchez-Guevara et al., 2015; Alkon et al., 2016). For these reasons, Sustainable Development Goal 7 focuses on ensuring that everyone has access to affordable, reliable, sustainable, and modern energy (Villavicencio Calzadilla and Mauger, 2018).

Household solid fuel use presents critical environmental, health, and development challenges. A key measure to address this issue is transitioning from solid fuels (e.g., coal and biomass) to clean energy (e.g., electricity, liquefied petroleum gas (LPG), and natural gas).[1] Various programs have been implemented to promote this transition around the world. In Ecuador, the government has initiated an energy-efficient

* Corresponding author.
E-mail address: xiang.zhang7@mail.mcgill.ca (X. Zhang).

[1] In this paper, we define "clean energy" primarily based on whether it contributes to air pollution in households. It's important to note that we do not consider whether the energy used to generate electricity is "clean", such as whether it's generated from coal-fired or renewable sources, as a criterion for defining clean energy.

https://doi.org/10.1016/j.jclepro.2024.141871
Received 17 January 2024; Received in revised form 4 March 2024; Accepted 22 March 2024
Available online 22 March 2024

cooking program, incentivizing 3.5 million households to install and use induction stoves by 2023 (Gould et al., 2018). Nigeria explored a consumer market for ethanol cookstoves, aiming to cover 0.5 million households in Lagos by 2019 (Quinn et al., 2018). In India, the Pradhan Mantri Ujjwala Yojana Program distributed 35 million free LPG connections by April 2018 (Dabadge et al., 2018; Kalli et al., 2022). In Bangladesh, the "solar home system program" installed 5.6 million home solar panel systems, providing electricity to about 22 million rural populations, increasing the national electricity penetration rate to 97% in 2020 (Cabraal et al., 2021). China has undergone a series of rural household energy transition programs to improve the energy quality as well as infrastructure development for expanding modern energy accessibility (Carter et al., 2020). Some of the most representative programs are the rural electrification project that has continued since the 1950s and National Improved Stove Program (NISP) since early 1980s (Sinton et al., 2004; Bie and Lin, 2015). By 2016, 100% of China's population had access to electricity (Yang, 2021).

These programs significantly contribute to the energy transition for cooking and lighting, yet China still relies on solid fuels for rural heating (Zheng and Wei, 2019). Over 100 million rural households consumed around 200 million tons of coal for space heating in 2015 (Energy Foundation China and Building Energy Conversation Research Center of Tsinghua University, 2022). China's "clean heating program," firstly announced in 2013 in Beijing, bans rural households from using coal and subsidizes the transition to electricity and natural gas for clean space heating. By 2021, over 26 million rural households participated in this program (Energy Foundation ChinaBuilding Energy Conversation Research Center of Tsinghua University, 2022; Zhang et al., 2019; He and Li, 2020). As forecasted by Ma et al. (2023), the integration of electric cooking and air source heat pumps for heating in rural households by 2060, as part of a carbon-neutral pathway, is anticipated to yield substantial health benefits and positive economic outcomes across the majority of Chinese provinces.

It is widely believed that policies are necessary to accelerate the transition to clean energy globally. But how much time do these policies "save" in the transition process? If the transition relied solely on general social and economic development, how long would it take to occur? The "energy ladder" and "energy stacking" theories propose that households transition from traditional solid fuels to cleaner sources as their socioeconomic status improves (Hosier and Dowd, 1987; van der Kroon et al., 2013). Empirical studies indicate that this transition is not always a discrete, one-way shift and that households often continue to use inferior fuels even as they adopt cleaner ones (Masera et al., 2000; Maina et al., 2017; Carter et al., 2020; Zheng, 2022).

Most studies in China on rural household energy transitions focus on describing energy use in specific administrative areas (e.g., county and province) or comparing differences across areas using cross-sectional survey data (Jiang and O'Neill, 2004; Wang et al., 2017; Wu et al., 2017; Hou et al., 2017; Wang and Jiang, 2017; Hou et al., 2019). Several recent studies have also used longitudinal surveys to understand factors related to energy transitions over time (Zhou et al., 2009; Tang and Liao, 2014; Ma and Liao, 2018; Tao et al., 2018; Liao et al., 2019; Carter et al., 2020; Zheng, 2022). For instance, Tao et al. (2018) conducted a nationwide survey in rural China in 2012 that included nearly 35,000 households. Using retrospective self-reported data, they examined the energy mix patterns for cooking and space heating across all Chinese provinces from 1992 to 2012. They found that, compared with the rapid transition for cooking, the energy transition for space heating is slow. Using per capita income, heating demand days, and coal prices at the provincial level, they found that these explanatory variables had a better degree of explanation for the variation in cooking energy transition compared to heating. In their follow-up study using data from a 2017 survey, which encompassed approximately 57,000 rural households spanning all provinces of mainland China, they found that despite a promising decline in the usage of biomass for both cooking (41%) and space heating (59%) purposes compared to levels observed in 2012, coal continued to hold a dominant position in fulfilling space heating needs (Shen et al., 2022). Most of these studies, based on cross-sectional or short-panel field survey data, span less than five years. This time scale limitation from surveys prevents us from understanding the temporal trend of "business as usual (BAU)" energy transition.

The use of administrative data from statistical offices offers an unparalleled advantage in analyzing national and provincial energy transition trends in this regard. Studies utilizing administrative statistics from the China Energy Statistical Yearbook and China's Rural Energy Yearbook, released by the Ministry of Agriculture, have rigorously analyzed temporal trends on the national or provincial level (Wang and Feng, 1997; Zhou et al., 2008; Yao et al., 2012; Zhang and Guo, 2013; Han et al., 2018; Zhang et al., 2022). For instance, Han et al. (2018) utilized province-level panel data from administrative statistics between 1991 and 2014 to reveal that, during this period, the rural household energy transition in China followed the "fuel stacking" pattern, with traditional commercial energy and advanced commercial energy having weak substitution effects on biomass energy. However, administrative data have been largely overlooked in recent studies in this field.

Several factors contribute to this situation. Firstly, the China Energy Statistical Yearbook, which is the most important administrative data in this field, does not include non-commodity energy (i.e., biomass fuels) quantities. We pursue this issue in the next section. Second, it is commonly understood that these statistics severely underestimate coal usage due to the fragmentation and complexity of rural household purchase sources (Cheng et al., 2017). Zhang et al. (2009) detailed the causes of this concern from the perspective of the different statistical methods of commercial and non-commercial energy data. Specifically, non-commercial energy data are typically gathered by the Ministry of Agriculture via its network of offices at the provincial, county, and township levels, while commercial energy data are typically obtained by the National Statistics Bureau through an annual survey of rural households (Li et al., 2019). Nevertheless, the unique advantages of administrative energy statistics include: first, they are the most comprehensive and representative and have the longest time series among available rural household energy data for China; second, they are publicly available; third, and perhaps most importantly, they represent the information that was available to public policy makers designing government intervention.

Our study tackles data concerns regarding incomplete and inconsistency by integrating all publicly available administrative energy statistical data sources. To shed light on rural household energy transition in China, we approach the following research questions: (1) What are the trends and characteristics of rural household energy transition on national and provincial levels in past decades in China? (2) How would a clean energy transition progress based on general economic growth without interventions? (3) What is the timeline for provinces in different energy use zones to achieve energy transition, and how much can interventions (like the "clean heating program") accelerate this process? By examining these questions, we aim to provide insights into the past trends, current state, and future prospects of China's rural household energy transition, as well as the potential impact of intervention programs.

Our study contributes to the existing literature on rural household energy use in China in the following ways: First, we provide a comprehensive integration of administrative statistics. By combining all publicly available administrative statistics on rural household energy data in China, we offer an extensive description of past trends in the field. Second, we present circumstantial evidence of the discrepancies between energy transitions in cooking and heating within the framework of the Chinese rural domestic energy use zone. Third, employing a time-series approach, we forecast the timeline of the energy transition, emphasizing the necessity and timeliness of interventions such as the "Clean Heating Program."

2. Data and methods

2.1. Data

Our analysis is based on provincial-level rural energy statistics in China from 1991 to 2018, focusing on data sources that include rural household energy use, population, and per capita income. By "rural household energy use," we refer in this paper to the quantities of biomass fuels (e.g., firewood, straw, and biogas), coal, electricity, and commercial gas fuels (e.g., LPG, and natural gas) used by rural households for such ends as cooking, space heating and cooling, lighting, and entertaining. Other energy sources that have not been widely used in rural China, such as dung and solar, are not included in this study.[2]

Our primary energy use data are from the China Energy Statistical Yearbook (CESY). It reports the energy use based on a top-down statistical method that starts with a high-level estimate of the total energy consumption of each energy type and then breaks it down into specific provinces and sectors. CESY focuses on commercially provided energy.[3] Existing studies note that biomass fuels, which are usually sourced locally by rural households, are often ignored or severely underestimated in the CESY. And while CESY data includes province-level rural household biomass fuel data based on a bottom-up[4] statistical method from the China Rural Statistics Report (CRSR, published by the Chinese Ministry of Agriculture between 1991 and 2007 and missing values for 1992–1994 and 1997), neither CESY nor CRSR have published province-level biomass fuel data past 2008. This has left a considerable gap in data coverage. To reflect the most current fuel use, we adopted datasets from two research reports: the China Building and Energy Saving Annual Report (CBESAR) for 2014 and 2018 (Building Energy Conversation Research Center, 2016, 2020) and the Typical Rural Energy Model (TREM) for 2015, published by Ministry of Agriculture and Rural Affairs as the supplement to the administrative data (Station of Agricultural Ecology and Resource Conservation, 2019).

We adopted different data strategies for the nation- and province-level analysis for our distinct research purposes. Our nation-level analysis emphasizes the temporal variation of various energy uses. We keep energy types consistent across years from the same data source. That is, the commercial energy data used for nation-level analysis, as well as the biomass fuel data up to 2008, are all obtained from CESY. As for the province-level analysis, the key indicator is the share of clean energy in total energy consumption. To guarantee the comparability of energy types for a province in a year, we adopted the data for a year of each province from the same source. Since the CESY has missing provincial data for several years prior to 2000, our data prior to 2000 for province-level analysis are uniformly derived from CRSR. The data after 2008 are from CBASER and TREM. To further discuss energy transition from the perspective of energy structure change, we include the number of rural households that rely on different fuels as their main domestic fuel source in each province from the first (1996) and third (2016) rounds of the China Agricultural Census (National Bureau of Statistics of China, 2016; National Bureau of Statistics of China, 1996).[5] The original data from CESY, CASR, CBASER, and TREM can be found in hard copies.[6] We manually entered these raw data to form a database for analysis. Table 1 shows the data sources used in the analysis to follow.

The province-level rural population and per capita income for each year are obtained from the webpage of the National Bureau of Statistics (National Bureau of Statistics of China, 2024).

To better contextualize our analysis, we situate our province-level analysis within the framework of China's rural domestic energy use zones. This zoning approach considers various factors such as climatic conditions, resource endowments, living habits, and socio-economic development levels, and groups the 31 provinces/municipalities of mainland China into seven distinct energy use zones, as indicated by the different colors in Fig. 1. Provinces within the same zone exhibit similar rural energy usage patterns, whereas there is significant variability across zones. One notable fact about household energy use in rural China is that households in extreme cold and cold zone provinces tend to consume more energy for space heating during the winter months, which generally span from November to April the following year. Additional detail on energy use zones differences in area, population, climate, and biomass resource use can be found in the Appendices.

2.2. Methods

To examine the temporal trends and characteristics of the BAU energy transition among rural households in China, we begin by exploring the relationship between rising per capita income and the share of clean energy used by rural households (as a proportion of their total energy consumption) through a two-way fixed effects model. Following this, we employ an Autoregressive Integrated Moving Average Model (ARIMA) to forecast the future trend of BAU energy transition in rural China until 2050, based on historical trends, without any additional interventions imposed.

2.2.1. Two-way fixed effects model

The majority of studies in this area use a discrete choice model (e.g., binary logit or multinomial probit model) to discuss factors related to rural household energy choice based on household-level survey data (Paudel et al., 2018; Takama et al., 2012; Wu and Zheng, 2022). Studies based on macro data have used stepwise multiple linear regression (Tao et al., 2018), double-hurdle (Shen et al., 2022), logarithmic mean Divisia index (Zhang and Guo, 2013), dynamic panel data (Han et al., 2018), and vector error correction models (Hao et al., 2018) to explore

Table 1
Data source of nation-level and province-level analysis.

Year	Nation-level Analysis	Province-level Analysis[a]
1991–1999	CESY	CASR
2000–2007		CESY
2014/2018	CESY (commercial energy), CBASER (biomass fuels)	CBASER
2015	CESY (commercial energy), TREM (biomass fuels)	TREM

[a] Due to the data constrains, Tibet, Hongkong, Macau, and Taiwan do not within the scope of this study.

[2] According to data from the third-round China Agricultural Census, the proportion of rural households utilizing solar energy as their primary energy source was only 0.2% in 2016, while the usage of other sources (including yak dung) stood at 0.5%. Tibet exhibited the highest utilization rates for these energy sources (solar: 1.2%, other: 48.3%), but we were unable to include it in the main analysis due to data availability constraints (refer to the footnote in the Data section below).

[3] By "commercial energy," we refer in this paper to the energy that rural households purchase from the market, which includes coal, electricity, and commercial gas fuels.

[4] The county agricultural bureaus collect data from rural households using field measurements and sample surveys, which are then reported to higher levels of agricultural administrative units in a cascading manner.

[5] The digital version of the first round China Agricultural Census data can be found on website of China Statistics Bureau (1996). Currently, the third round of China Agricultural Census data are only available in the hardcopy version.

[6] China's economic and social big data research platform provides a digital version of the CESY and CASR (China's economic and social big data research platform, 2023).

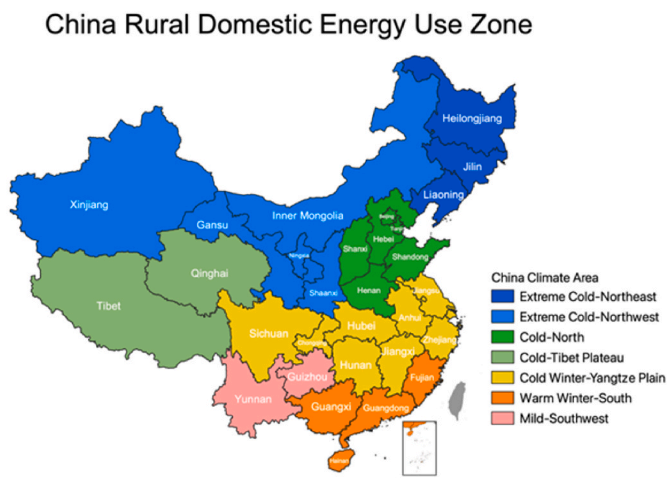


Fig. 1. Seven rural domestic energy use zones in mainland China.
(Notes: The zoning method uses a layer overlay approach by integrating China's Agricultural Climate Zoning, Building Climate Planning, China Rural Energy Comprehensive Zoning, and Rural Renewable Energy Zoning. In the extremely cold zones, the average temperature is usually below −10 °C in the coldest month, and there are generally more than 145 days with a daily average temperature below 5 °C; in the cold zones, the average temperature in the coldest month is between 0 and 10 °C and days with a daily average temperature below 5 °C is generally between 90 and 145 days.).

the factors related to rural energy consumption and transition. We use a two-way fixed effects model to estimate the correlation of per capita income growth on the BAU energy transition of provinces in the different energy use zones. The two-way fixed effects model has commonly been used for causal inference with panel data (Imai and Kim, 2021). Here we use a simple two-way fixed effects model to address bias caused by possible unit- and time-invariant unobservable factors. We include two fixed effects terms for province and year. Equation (1) shows the two-way fixed-effects model we use in this study:

$$Share_{i,t,z} = \beta_z \, Income_{i,t,z} + Province_{i,z} + Year_t + \varepsilon_{i,t,z} \tag{1}$$

where the dependent variable $Share_{i,t,z}$ is the percentage of clean energy in total rural domestic energy consumption for province i in energy use zone z and year t, the independent variable $Income_{i,t,z}$ is the rural per capita income for province i in energy use zone z and year t (unit: 1000 RMB), $Province_{i,z}$ is the fixed effect term for province i in energy use zone z, $Year_t$ is the fixed effect term for year t, and $\varepsilon_{i,t,z}$ is the error term. The coefficient β_z represents the share of clean energy changes associated with a 1000 RMB increase in rural per capita income for energy use zone z. The coefficient β_z is calculated using the within estimation. We conduct this regression analysis separately for each domestic energy use zone.

$Share_{i,t,z}$ is the clean energy fraction, defined in Equation (2), [7]:

$$Share = \frac{C_{clean}}{C_{total}} = \frac{C_{gas} + C_{elec}}{C_{coal} + C_{biomass} + C_{gas} + C_{elec}} \times 100\% \tag{2}$$

2.2.2. Autoregressive integrated moving average (ARIMA) model

Examining the historical association between income and the BAU shift towards energy sources prior to any policy intervention allows us to predict how an energy transition would have played out in the absence of such a policy. Predicting the trajectory of the BAU transitions provides a counterfactual scenario by which we can judge the effectiveness of attempts to accelerate the process. Among methods for developing such predictions, three commonly employed methods are regression-based formulation, artificial neural networks, and time series models (Kuster et al., 2017). In particular, time series models (e.g., ARIMA) perform well for medium and long-term predictions (Wang et al., 2018).

We use an ARIMA model to predict the BAU rural household energy transition for provinces in different energy use zones in the future. One advantage of ARIMA is that it only requires the past values of the predicted variable itself (share of clean energy in this study), without resorting to exogenous variables (e.g., indicators such as economic development and energy prices) to carry out prediction (Wang et al., 2018). An ARIMA(p,d,q) model incorporates differencing, autoregression, and moving average models as shown in Equation (3).

$$y'_t = c + \varphi_1 y'_{t-1} + \ldots + \varphi_p y'_{t-p} + \theta_1 \epsilon_{t-1} + \ldots + \theta_q \epsilon_{t-q} + \epsilon_t \tag{3}$$

In Equation (3), y'_t on the left side is the differenced series which is the change between consecutive observations in the original series. Differencing helps stabilize the mean of a time series. The degree of differencing (d) specifies the number of times the data have been differenced in the ARIMA(p,d,q) model. For example, in an ARIMA(p,1,q) model where $d = 1$, $y'_t = y_t - y_{t-1}$; in an ARIMA(p,2,q) model where $d = 2$, $y'_t = (y_t - y_{t-1}) - (y_{t-1} - y_{t-2})$. In practice, it is almost never necessary to go beyond second-order differences ($d \leq 2$) (Hyndman and Athanasopoulos, 2018).

The "predictors" on the right side include both lagged values of y_t and lagged errors. The autoregression model ($\varphi_1 y'_{t-1} + \ldots + \varphi_p y'_{t-p}$) predicts the future energy transition based on the lagged values of clean energy share. The order p in the ARIMA(p,d,q) model indicates that the lagged values (y_t) of the previous p years are included in the autoregression model. The moving average model ($\theta_1 \epsilon_{t-1} + \ldots + \theta_q \epsilon_{t-q}$) predicts based on the lagged forecast errors in a regression-like model. The order q in the ARIMA(p,d,q) model indicates that the lagged forecast errors of q previous years are included in the moving average model. c is the mean value of the time-series data and ϵ_t is the error term.

Different choices of the parameters (i.e., p, d, q) in the ARIMA(p,d,q) model represent different possible models. We use the "auto.arima" function in the R "forecast" package (Hyndman and Khandakar, 2008; Hyndman et al., 2022), which determines the optimal parameters (p,d,q) combining unit root tests, minimization of Corrected Akaike's Information Criterion (AICc) and Maximum Likelihood Estimation (MLE) after going through different parameter combinations. See the Appendices for details on ARIMA parameters for different energy use zones.

To prepare the data for ARIMA analysis, we addressed missing values in the share of clean energy for each domestic energy use zone between 1994, 1997, and 2008–2014, which are 14 missing values for C-T and 10 missing values for other zones, using linear interpolation to replace missing values with the "imputeTS" package in R (Moritz and Bartz-Beielstein, 2017).

3. Results & discussion

3.1. National level rural household energy transition in China between 1991 and 2018

We begin by examining the historical trends in China's rural domestic energy sector over the past 30 years at the national level, as shown in Fig. 2. In terms of energy consumption, to prevent optimistic estimates of energy derived from the decrease in total solid fuels due to rural depopulation accompanying urbanization, we have selected per capita consumption as an indicator. Concurrently, this metric can capture shifts in the energy mix within households, thereby offering insights into the health impacts of indoor air pollution. Fig. 2a indicates a continuous increase in per capita energy consumption, reaching 600 kg coal equivalent (kgce) in 2018, which is twice the amount consumed in 1996. The different colors in the plot represent various energy sources

[7] All energy consumptions in Equation (1) are converted to their coal equivalent; detailed estimates are provided in Appendices.

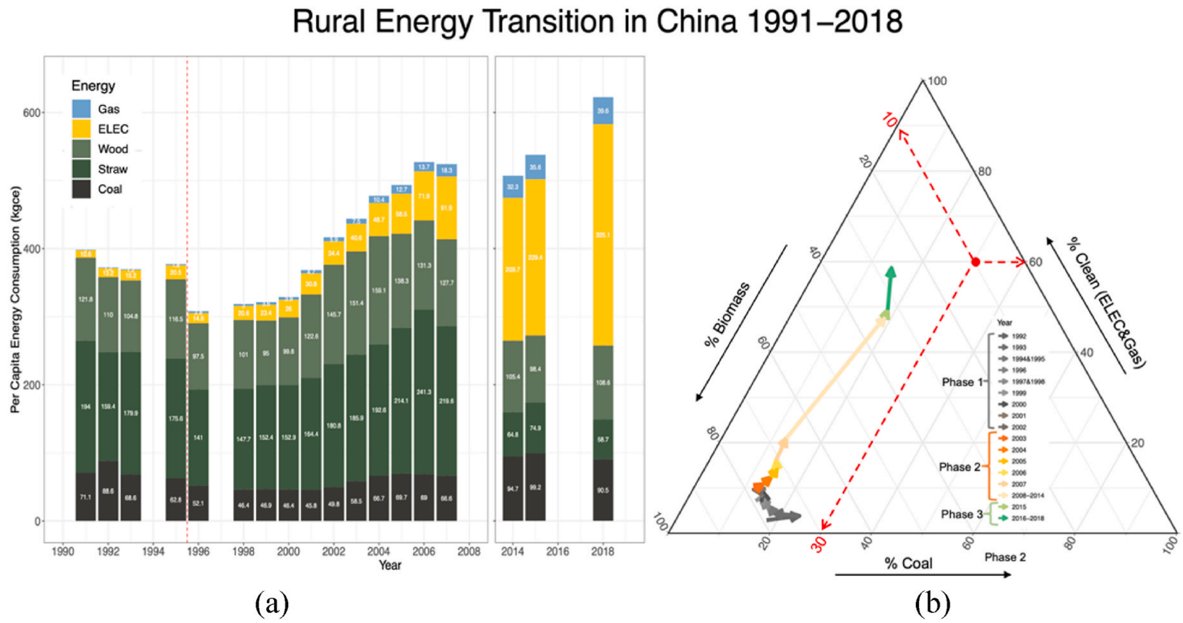


Fig. 2. Rural household energy transition in China 1991–2018.
(Note: Each arrow in Fig. 2b represents the change in these three dimensions (i.e., Biomass, Coal, and Clean) over a specific timeframe (usually one to several years, based on data availability). These arrows depict the starting and ending points, with the former showing the share of each energy type in total consumption at the period's beginning and the latter indicating the share at the end. The employed color scheme further categorizes these changes into three identified transition phases: Phase 1 (gray), Phase 2 (orange), and Phase 3 (green). The red dot and red dashed lines are to guide interpretation, i.e., to obtain the proportions of Biomass, Coal, and Clean corresponding to any given arrow. For instance, the red dot in the figure represents the proportion of Biomass, Coal, and Clean for 10%, 30%, and 60%, respectively.).

and reflect the changes in the energy structure. Notably, commercial energy (i.e., coal, electricity, LPG, and natural gas) consumption has consistently risen over the past two decades, particularly clean energy (i.e. electricity, LPG, and natural gas). Of these, electricity consumption has grown the fastest, reaching 325 kgce per capita in 2018, which is twenty times the amount consumed in 1996. Electricity has become the dominant source of domestic energy consumption, accounting for more than 50% of total energy consumption in 2018.

While gas consumption has increased tenfold in 20 years, it only accounts for about 5% of energy consumption. LPG remains the most widely used gas fuel in rural China due to its efficiency, ease of transport, and affordability. Other gas fuel types, such as natural gas and biogas, are not as popular due to resource shortages and transmission constraints (Economides and Wang, 2010). Over the past 20 years, while commercial energy consumption has been growing rapidly, the share of coal in China's rural domestic energy mix has remained low at around 15%. This is primarily because household coal consumption is concentrated in a few provinces in North China and is mainly used for space heating (Wu et al., 2019).

Contrary to the rapid growth of commercial energy in the last two decades, the per capita consumption of biomass fuels has continued to decline. The consumption of firewood and straw was 122 and 194 kgce in 1991; their consumption reduced to 109 and 59 kgce in 2018, respectively. The decline in the consumption of biomass fuels is mainly due to the substantial decrease in straw. In contrast, the absolute value of per capita firewood consumption has remained stable for thirty years. The share of biomass fuels in per capita energy consumption has dropped from over 80% in the 1990s to only about 25%.

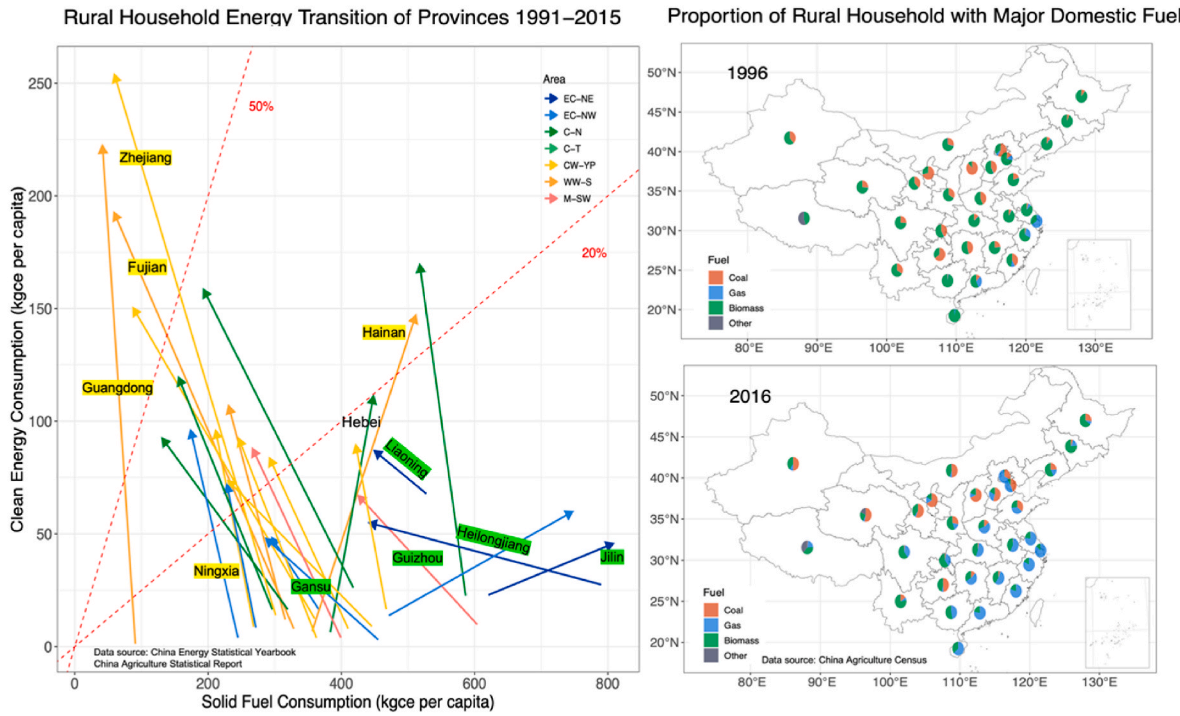
The ternary plot (Fig. 2b) reflects the evolution of China's rural energy mix over the last three decades. The arrows indicate the direction of the transition, which has moved from solid fuels (coal and biomass fuels) to cleaner energy (gas and electricity). The colors of the arrows represent the three phases of the rural household energy transition from 1991 to 2018. We see that an early period, which we call Phase 1 (1991–2002), saw a slow transition with almost no change in biomass (−1%), a minor decrease in coal (−6%), and slight increases in clean energy (+7%). Clean energy only contributed around 10% to rural domestic energy consumption during this period. Phase 2 (2003–2015) was a "commercial transition" period, with biomass fuels decreasing by 44% and a rapid increase in commercial energy. The popularity of clean energy, specifically electricity, drove this transition. The share of coal in the rural domestic energy mix only increased by about 8% during this period. Phase 3 (2015–2018) was a "clean transition" period. Around 2012, the Chinese government turned more attention to combatting air pollution, specifically $PM_{2.5}$ pollution, leading to a number of energy transition programs for rural households that began in 2015. These programs, such as the "coal to electricity" and "coal to natural gas" projects in the North China Plain and the Fenwei Plain, were localized but had a national impact. In only three years, the share of biomass fuels and coal reduced by 10% and 5%, respectively.

The figure also shows the acceleration of the energy transition rate in China's rural household sector. From 1991 to 2015, with no significant intervention project, the transition to clean energy progressed by only 5% in the first decade and about 40% in the second decade. The question now is whether this trend will continue at a sustained and rapid pace or encounter bottlenecks, which we will explore in the following sections.

3.2. *Provincial level rural household energy transition in China*

In the previous section, we discussed the temporal trends in the energy transition of rural households at the national level. This section investigates geographic differences in that overall picture.

Fig. 3a illustrates the energy transition at the province level located in different energy use zones from 1991 to 2015. The two red dotted lines in the figure provide a reference for the degree of energy transition. At the base of the arrows, representing the year 1991, there are significant differences between provinces in per capita total energy consumption. For instance, provinces in the Extreme Cold-Northeast zone (EC-NE) have a per capita consumption of solid fuels that is over 500 kgce, approximately double that of provinces in other zones, while per



(a) (b)

Fig. 3. Province-level rural household energy transition 1991–2015.
(Notes: Each arrow in Fig. 3a only represents the situation in 1991 and 2015, respectively. The arrows do not indicate any intermediate years between 1991 and 2015. The pie charts within Fig. 3b show the share of rural households' main source of domestic fuels, which is obtained by dividing the number of households by their primary source of domestic fuel by the total number of registered households in each province. "Other" in Fig. 3b is the proportion of households using solar energy and yak dung, etc., as their main source of domestic energy source. All proportions were calculated based on the household number after removing households who reported electricity as their primary source.).

capita clean energy consumption is less than 50 kgce in almost all provinces. Between 1991 and 2015, most provinces witnessed an increase in per capita energy consumption accompanied by a decrease in solid fuel consumption, as indicated by the heads of the arrows. Per capita consumption of solid fuels only increased in four provinces in 2015, namely Heilongjiang, Jilin, Hainan, and Hebei, with two provinces in the EC-NE showing significantly larger increases.

Per capita clean energy consumption increased in all provinces compared with 1991, particularly in the Cold Winter-Yangtze Plain (CW-YP) and Warm Winter-South zones (WW-S), where clean energy consumption per capita exceeded 200 kgce in Zhejiang and Guangdong in 2015. In 1991, the share of clean energy in rural domestic energy consumption was far below 20% in all provinces. However, compared with 1991, this share increased in all provinces, especially for provinces in CW-YP and WW-S, where it exceeded 50%. In contrast, the share of clean energy is still lower than 20% for all provinces in EC-NE and most in EC-NW in 2015.

The extent to which the share of clean energy has increased varies greatly across different regions, as indicated by the positions of the arrow ends in Fig. 3a. The provinces with the highest and lowest transition degrees between 1991 and 2015 are highlighted with yellow and green text labels, respectively. Notably, the four provinces (Zhejiang, Fujian, Guangdong, and Hainan) with the highest transition degree are located in the CW-YP and WW-S zones, while the four provinces (Jilin, Heilongjiang, Liaoning, and Gansu) with the lowest degree are situated in the Extreme Cold zones, where intense winter space heating demands limit energy transition. Consequently, the clean energy transition on a national level has been primarily driven by the progress in WW-S and CW-YP provinces, while the transition in EC-NE and EC-NW provinces has remained largely stagnant for decades.

We use two maps, shown as Fig. 3b, to further show the energy transition in major household fuel at the provincial level. These two maps are based on CAC data.[8] The upper figure in Fig. 3b shows that biomass fuel was the dominant fuel for rural households in most provinces in 1996, especially for provinces in EC-NE and WW-S. For Hainan and Guangxi in WW-S, over 95% of rural households took biomass as their primary domestic fuel in 1996. Only in a few provinces, over 50% of households took coal as the primary domestic fuel like Shanxi, Ningxia, and Guizhou, which have rich coal resources. A particular case is Shanghai, which has few rural residents and higher socioeconomic status on average; about 66% of its rural households used gas fuel as their primary domestic fuel even in 1996. The bottom figure in Fig. 3b shows the share of rural households relying on different domestic fuels for provinces in 2016. The primary domestic fuel of each province has changed considerably; meanwhile, this change varies geographically. Gas fuel has been the primary domestic fuel for most rural households in Southeastern Provinces in WW-S and CW. In a few WW-S and CW provinces in Southwestern China, like Chongqing and Yunnan, even though over half of rural households still use biomass as their major domestic fuel, the proportion of households that mainly use gas fuels has reached almost 40%. There is also a greater share of households that use gas fuels as their primary fuel in EC-NW and C-N provinces; the share of rural households that use coal as their major fuel also increases significantly in these provinces. Compared with 1996, coal replaced biomass as the most common fuel in EC-NW provinces except Shaanxi in 2016. As we previously discussed, the pace of energy transition in EC-NE provinces is slow. The share of rural households that take solid fuel gas as

[8] To keep the consistency of these two rounds of data, we did not include the number of households that use electricity as their major energy source since that was only reported in 2016 data.

primary fuel is still 82%, 83%, and 92% in provinces Liaoning, Jilin, and Heilongjiang, respectively. A notable observation is the prevalence of electricity as a primary energy source among rural households, a factor not included in our analysis due to data consistency concerns. According to the third-round China Agricultural Census (CAC) data, 59% of rural Chinese households rely on electricity as one of their primary domestic energy sources in 2016, with usage rates varying from 3% in Xinjiang to as high as 88% in Guizhou.[9]

This section delved into the energy transition of rural households at the provincial level, examining both the quantity and structure of the transition. The significant regional disparities between provinces with and without heating demand suggest a higher dependence on solid fuels for heating compared to cooking. As a result, the shift towards clean energy in C and EC zones poses greater challenges. Moreover, these regional disparities also foreshadow potential bottlenecks in the nationwide energy transition, as provinces in the EC and C zones may stall after the warmer provinces have completed their transitions.

3.3. Role of income in the rural household BAU energy transition

Apart from the climatic conditions and corresponding energy needs mentioned above, household income is widely recognized as a critical determinant of the energy transition, clean energy adoption, and suspension of solid fuel use in existing studies (Lewis and Pattanayak, 2012; Guta et al., 2022). With more advanced fuels offering benefits such as time-saving, better living conditions, and improved health, households gravitate toward improved fuels once increased income expands their choice set on energy sources. In this section, we examine the relationship between per capita income and rural household energy transition in different domestic energy use zones. Our analysis provides insights into whether we can expect a BAU energy transition in the near future, given the historically high income growth rate of around 10% per year in rural China.

Fig. 4 summarizes the regression results from the two-way fixed effect model estimating the role of per capita income in rural household energy transition. As shown in Fig. 4, per capita income generally plays a more critical role in rural household energy transition for provinces without space heating needs in winter, especially for M-SW and WW-S provinces. Every 1000 RMB[10] increase in per capita income is associated with about 11% and 5% increase in the share of clean energy in M-SW and WW-S provinces, respectively. The greater effect size of these coefficients suggests an optimistic scenario of BAU transition in provinces in these two zones. However, it seems relying on income growth to achieve BAU energy transition would present a bleak prospect for provinces with space heating needs. In these provinces yearly low temperatures between −20 °C and −10 °C and moderate heating demands (C-N and C-T), a per capita income increase of 1000 RMB is only correlated with a modest increase of 0.60%–0.77% in clean energy share. In EC provinces with lowest temperatures below −20 °C and intensive heating demands, the magnitude of correlation further decreases to approximately zero or even negative. The negative confidence interval for EC-NE can be attributed to the significant heating demand and the traditional heating method of burning solid fuels, such as the kang, in this zone. As income increases, households tend to use more solid fuels to achieve better heating effects. As a result, the proportion of clean energy decreases with rising income, as solid fuel consumption increases faster than that of clean energy. In other words, within the income range covered in this study, the income effect on solid fuel demand is greater than the substitution effect towards clean energy.

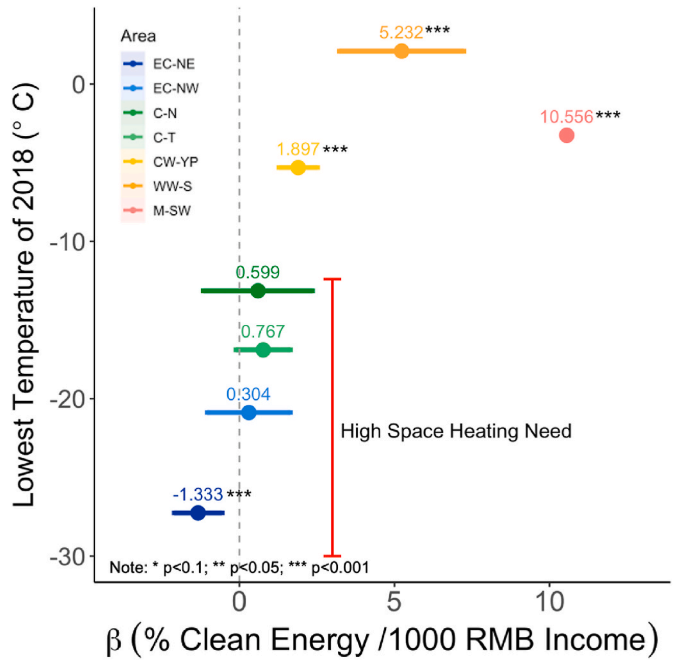


Fig. 4. Coefficients and confidence intervals of two-way fixed effects model. (Notes: The sample used in this study is an unbalanced panel of provinces. To report our findings, we have listed the estimations of coefficients and 95% confidence intervals in descending order of the winter 2018 minimum temperatures in each domestic energy use zone. The confidence intervals are based on robust standard errors. We detail the regression results in Appendices.).

It is worth noting that in most regression models we analyzed, the R^2 value is less than 0.1, indicating that per capita income explains only a minor portion of the BAU energy transition in most provinces. Considering the time-sensitive nature of policy objectives and the current low share of clean energy, the small coefficients in zones with space heating needs suggest that intervention programs will be necessary to accelerate the transition in those provinces.

3.4. Timelines of BAU energy transition

In the previous section, we discussed the role of per capita income growth in the rural household BAU energy transition. Based on our results, it appears to be hard for provinces with space heating needs in rural areas to achieve energy transition solely relying on income growth. The Chinese government has set up a series of environmental and climatic targets to "reach carbon peak in 2030, globally reach the air quality target in 2035, and achieve carbon neutrality in 2060" (Shi et al., 2021). Nevertheless, trajectory the advancement of the social economy and the widespread adoption of commercial energy sources, China's rural residential coal consumption surged from 69 million tons in 1985 to 73 million tons in 2015 (National Bureau of Statistics of China, 2016; Zhao et al., 2022). This poses a serious challenge to the achievement of carbon emissions and air quality objectives. Therefore, achieving a rural household energy transition, especially a reduction in total coal consumption, in a shorter period is necessary. As a final way to set up a counterfactual of a world in which no policies were enacted, we predict the timeline for transition in different energy use zones based on their historical pre-policy implementation trends.

Fig. 5 shows the predicted energy transition for different energy use zones from 2018 (2014 for C-N) to 2050, using predictions from the ARIMA models based on historical trends beginning in the early 1990s. The dotted lines and shaded areas in the figure represent the BAU scenario, which indicates the share of clean energy without intervention. As our previous findings suggest, provinces in WW-S, CW-YP, and M-SW

[9] Please refer to the map illustrating the complete third-round census data on the "proportion of rural households with primary domestic energy sources," including electricity, in the Appendices.

[10] According to Purchasing power parity (PPP) conversion factor 2021 (http://wdi.worldbank.org/table/4.16), 1000 RMB is equivalent to 238.66 US dollars.

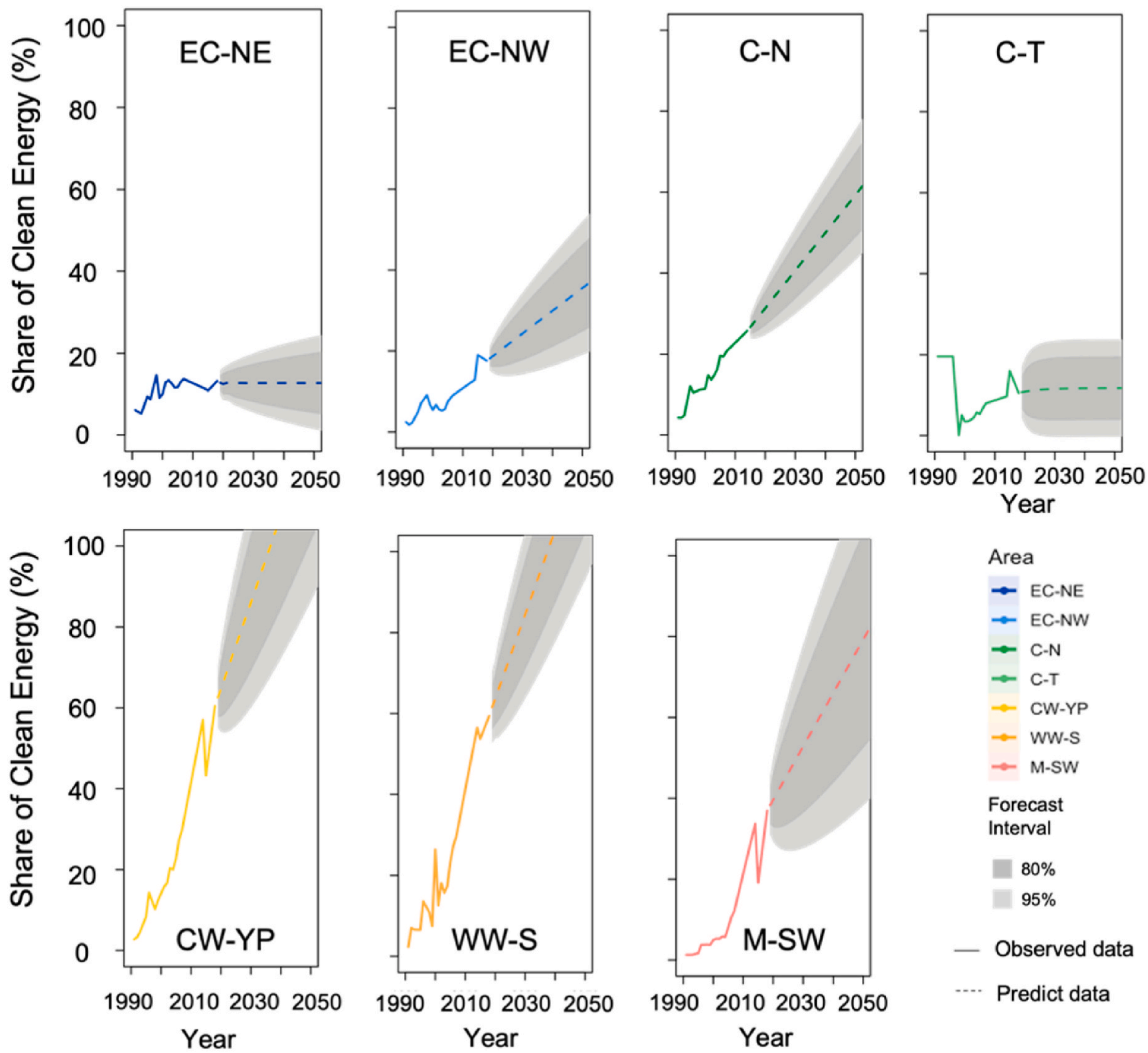


Fig. 5. Predicted timeline of BAU rural energy transition.
(Note: The ARIMA(d,p,q) model predicts rural household energy transitions separately for different domestic use zones in the coming decades, using different parameters. The flat dotted lines in EC-NE and C-T indicate that no significant temporal patterns were identified in these regions.).

which do not require intensive space heating would have expected to complete a full energy transition earlier. According to the prediction results, provinces in CW-YP and WW-S regions would have achieved complete energy transition in rural households before 2050. Even under the conservative estimates of the 95% confidence interval, the share of clean energy in these two areas would have reached about 80%. Although energy transition in M-SW provinces would have occurred a bit later, it has shown a fast pace in recent years, which may have put it on a path toward an estimated share of clean energy of around 80% in 2050. In optimistic estimates, all provinces without intensive space heating demands are likely to complete rural household energy transition.

However, for provinces in EC and C zones that require intensive space heating, only those in C-N would have been expected to make measurable progress in the coming decades, perhaps approaching around 70% by 2050. This may be attributed to several factors, including mild space heating needs compared to other EC and C-T provinces, households being more affluent, and administrative pressure caused by severe air pollution in the area (which spurred several small-scale energy interventions in the recent decade like the "Sending LPG to Villages" program in Beijing). The transition to clean energy in rural households across the EC provinces, especially EC-NE, would have been prolonged into the coming decades. Even under an optimistic scenario, the proportion of clean energy in the EC-NE areas is forecasted to remain below 20% by 2050 (at the high end of 95% confidence interval). Unfortunately, the provinces in C-T have the least favorable outlook. Limited infrastructure and unfavorable topography make it challenging to transport clean energy to the region, while low incomes make it difficult for households to afford advanced clean energy. These factors are slowing down the pace of the energy transition, with the proportion of clean energy likely to be less than 20% in 2050. These findings highlight the uneven distribution of energy transition progress across different zones, and suggest urgent interventions are needed, particularly in provinces with high space heating demands, to meet the air quality and climate change goals within the government's announced timeframe.

In 2015, the Beijing-Tianjin-Hebei area, a region with some of the worst air pollution in the world, implemented a large-scale "clean heating program" to promote rural household energy transition. Fig. 6 compares the share of clean energy in the rural household sector between the predicted transition, from the ARIMA results, and observed values in 2018 to illustrate the potential effects of the heating energy intervention on the energy transition in C-N. The observed clean energy share in Beijing, Tianjin, and Hebei (shown as red triangles) was about

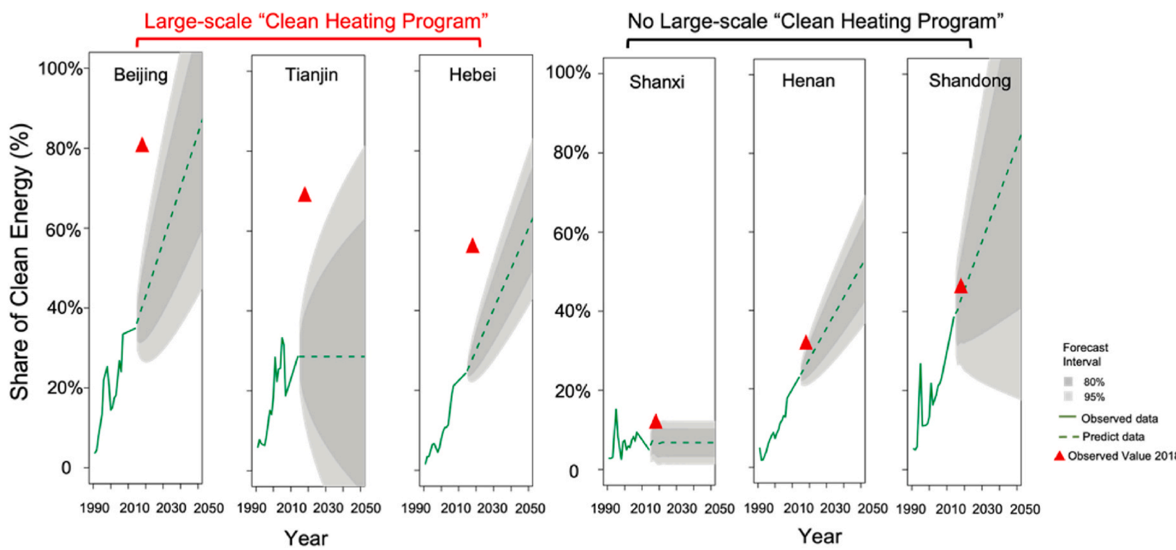


Fig. 6. Predicted timeline of BAU rural energy transition for C-N provinces.
(Note: The ARIMA(d,p,q) model predicts rural household energy transitions separately for different provinces, using different parameters. The flat dotted lines of Tianjin and Shanxi provinces indicate no significant temporal patterns, mainly due to the great fluctuation identified in these provinces.).

40%, 40%, and 27% higher than the predicted values, respectively. In contrast, the observed values in the other three provinces in C-N (Shanxi, Henan, and Shandong) without large-scale interventions were similar to the predicted values. These results indicate that the heating intervention may have a significant impact on promoting clean energy in the Beijing-Tianjin-Hebei area. Overall, these findings suggest that large-scale interventions, such as the clean heating program, may be necessary to accelerate the energy transition in highly polluted regions.

From a timeline perspective, the "clean heating program" has advanced the energy transition by at least 10 years for Beijing, Tianjin, and Hebei compared to the high end of the 95% confidence interval. Even though there are many debates about the program like increased financial burden to households from increased electricity expenditures and energy supply shortages from increased demand on the grid, the "clean heating program" has shown great effectiveness in driving an energy transition in the rural household sector (Hu, 2021). These results suggest the great potential for interventions to replace the burning of solid fuels for heating through clean energy in driving the rural household energy transition in EC and C provinces.

3.5. Discussion

The household energy transition is crucial for sustainable development in the developing world. However, the scarcity of high-quality statistical data on rural household energy use, particularly in China, has severely impeded research in this area (Niu et al., 2019). Several issues plague China's statistical data on rural household energy use. Firstly, non-commercial energy sources are omitted. The two primary data sources, the China Energy Statistical Yearbook and the China Rural Statistics Report, ceased publishing biomass fuel consumption quantities after 2008. Furthermore, energy sources like yak dung and solar energy, prevalent in northwestern provinces such as Tibet, Xinjiang, and Qinghai, have never been included in these datasets (Rhode et al., 2007; Fang and Wei, 2013). Consequently, there is limited understanding of these non-commercial energy sources and their roles in energy transition within these provinces. Secondly, there is no distinction between energy activities. Previous studies have highlighted significant disparities in energy use and transition patterns for cooking and space heating (Tao et al., 2018; Shen et al., 2022). However, existing administrative statistics fail to differentiate energy consumption quantities between these activities. To address this issue, we conducted our analysis within the context of the China Rural Domestic Energy Use Zone, aiming to provide indirect insights into the energy transition of different activities. Although datasets such as the WHO's Household Energy Dataset cover relatively long-time scales and differentiate between cooking and heating energy consumption, their sample representativeness could be improved. Thirdly, there is inconsistency in energy indicators. Across the three rounds of the Chinese rural censuses, indicators of domestic energy use varied. The first round excluded electricity as an option, the second round reported primary and secondary cooking, as well as space heating and cooling energy separately, while the third round returned to the primary domestic energy source but also allowed households to select up to two energy sources, including electricity. Such inconsistency severely impedes temporal analysis using census data. Given these challenges with administrative statistics, which are difficult to resolve in the short term, long-term scales based on representative extensive sample survey data will continue to play an essential role in this field.

To address the challenge of data scarcity, we integrated all publicly available administrative statistics along with data from research reports. Despite employing flexible data strategies in various analyses to improve data comparability, the complexity of data sources inevitably introduced uncertainty into our results. However, reassuringly, our diverse data sources exhibited no significant discrepancies in magnitude, with observed past trends aligning with existing studies (Zhang et al., 2009; Han et al., 2018; Niu et al., 2019). Nevertheless, this uncertainty regarding historical trends inherently influences our future predictions. Therefore, alongside point estimates, we provide 80% and a more conservative 95% confidence interval. However, it is important to acknowledge that the simple time-series method used for future predictions based on past data also carries its uncertainties, particularly when dealing with limited data, as seen in our C-N six-province forecasts. The imperfect differences in data from different sources result in notably wide confidence intervals; therefore, caution must be exercised in interpreting the results of future predictions.

4. Conclusion

China's rural household sector has made significant progress toward clean energy over the past three decades, particularly in the last decade. However, the transition has been uneven across regions, with the Extreme Cold (EC) and Cold (C) zone provinces lagging behind the southern provinces. This disparity underscores the challenge of transitioning energy use for space heating purposes. Our regression analysis suggests that achieving a complete transition in the short term based solely on general economic development may be unrealistic for EC provinces. This means that without outside investment and policy intervention, the environmental, health, climate, and development issues caused by solid fuel combustion will continue to persist in these provinces. The "clean heating program" in Beijing, Tianjin, and Hebei has demonstrated significant potential to drive the energy transition in EC and C provinces. These interventions highlight the importance of investing in clean energy infrastructure and implementing large-scale policies to accelerate the transition in heavily polluted regions. In conclusion, the uneven transition across regions highlights the urgent need for continued efforts in implementing effective policy interventions for space heating. For China to meet its promised timeline and ambitious air quality and climate mitigation goals, it is crucial to accelerate the transition to clean energy in heavily polluted regions.

CRediT authorship contribution statement

Xiang Zhang: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christopher P. Barrington-Leigh:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Brian E. Robinson:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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.

Acknowledgments

This work was supported by Social Sciences and Humanities Research Council (SSHRC) grants (#430-2017-00998 and #435-2016-0531), Canadian Institutes of Health Research (CIHR, Canada's federal funding agency for health research) Project Grants (#148697 & #159477) and conducted under contract to the Health Effects Institute (HEI), an organization jointly funded by the United States Environmental Protection Agency (EPA) (Assistance Award No. R-82811201). We would like to express our gratitude to Jason Brown of the Federal Reserve Bank of Kansas City for providing us with valuable feedback at the 2022 North American Meetings of the Regional Science Council International. We wish to express our sincere gratitude to the Beijing Household Energy Transition (BHET) project team for their valuable suggestions. Additionally, we extend our appreciation to Ni Zhuo of the Zhejiang Academy of Agricultural Sciences for assisting us in our data collection.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141871.

References

Adkins, E., Oppelstrup, K., Modi, V., 2012. Rural household energy consumption in the millennium villages in Sub-Saharan Africa. Energy Sustain. Dev. 16, 249–259. https://doi.org/10.1016/j.esd.2012.04.003.

Alkon, M., Harish, S.P., Urpelainen, J., 2016. Household energy access and expenditure in developing countries: evidence from India, 1987–2010. Energy Sustain. Dev. 35, 25–34. https://doi.org/10.1016/j.esd.2016.08.003.

Bie, Z., Lin, Y., 2015. An overview of rural electrification in China: history, technology, and emerging trends. IEEE Electrification Mag. 3, 36–47. https://doi.org/10.1109/MELE.2014.2381606.

Biswas, S., Das, U., 2022. Adding fuel to human capital: exploring the educational effects of cooking fuel choice from rural India. Energy Econ. 105, 105744 https://doi.org/10.1016/j.eneco.2021.105744.

Building Energy Conversation Research CenterT.U., 2020. 2020 Annual Report on China Building Energy Efficiency. China Architecture Publishing & Meida Co. Ltd.

Building Energy Conversation Research CenterT.U., 2016. 2016 Annual Report on China Building Energy Efficiency. China Architecture & Building Press, Beijing.

Cabraal, A., Ward, W.A., Bogach, V.S., Jain, A., 2021. Living in the Light: the Bangladesh Solar Home Systems Story. World Bank. https://doi.org/10.1596/35311.

Carter, E., Yan, L., Fu, Y., Robinson, B., Kelly, F., Elliott, P., Wu, Y., Zhao, L., Ezzati, M., Yang, X., Chan, Q., Baumgartner, J., 2020. Household transitions to clean energy in a multiprovincial cohort study in China. Nat. Sustain. 3, 42–50. https://doi.org/10.1038/s41893-019-0432-x.

Cheng, M., Zhi, G., Tang, W., Liu, S., Dang, H., Guo, Z., Du, J., Du, X., Zhang, W., Zhang, Y., Meng, F., 2017. Air pollutant emission from the underestimated households' coal consumption source in China. Sci. Total Environ. 580, 641–650. https://doi.org/10.1016/j.scitotenv.2016.12.143.

Dabadge, A., Sreenivas, A., Josey, A., 2018. What Has the Pradhan Mantri Ujjwala Yojana Achieved So Far?, vol. 7.

Economides, M.J., Wang, X., 2010. Integrated use of natural gas in rural China. In: SPE Annual Technical Conference and Exhibition. OnePetro.

Energy Foundation China, Building Energy Conversation Research Center of Tsinghua University, 2022. China's Rural Coal Management Report 2022.

Fang, Y., Wei, Y., 2013. Climate change adaptation on the Qinghai–Tibetan Plateau: the importance of solar energy utilization for rural household. Renew. Sustain. Energy Rev. 18, 508–518. https://doi.org/10.1016/j.rser.2012.10.037.

Gould, C.F., Schlesinger, S., Toasa, A.O., Thurber, M., Waters, W.F., Graham, J.P., Jack, D.W., 2018. Government policy, clean fuel access, and persistent fuel stacking in Ecuador. Energy Sustain. Dev., Scaling Up Clean Fuel Cooking Programs 46, 111–122. https://doi.org/10.1016/j.esd.2018.05.009.

Guta, D., Baumgartner, J., Jack, D., Carter, E., Shen, G., Orgill-Meyer, J., Rosenthal, J., Dickinson, K., Bailis, R., Masuda, Y., 2022. A systematic review of household energy transition in low and middle income countries. Energy Res. Social Sci. 86, 102463.

Han, H., Wu, S., Zhang, Z., 2018. Factors underlying rural household energy transition: a case study of China. Energy Pol. 114, 234–244.

Hao, Y., Wang, L., Zhu, L., Ye, M., 2018. The dynamic relationship between energy consumption, investment and economic growth in China's rural area: new evidence based on provincial panel data. Energy 154, 374–382. https://doi.org/10.1016/j.energy.2018.04.142.

He, K., Li, X., 2020. China dispersed coal management report 2020. Natural Resource Defence Council 5–6.

Hosier, R.H., Dowd, J., 1987. Household fuel choice in Zimbabwe: an empirical test of the energy ladder hypothesis. Resour. Energy 9, 347–361.

Hou, B., Liao, H., Wang, J.-W., Wang, F., Zhang, H., 2019. Cooking fuel decision-making and family structure: a field study in China. Environ. Sci. Pollut. Res. 26, 24050–24061.

Hou, B.-D., Tang, X., Ma, C., Liu, L., Wei, Y.-M., Liao, H., 2017. Cooking fuel choice in rural China: results from microdata. J. Clean. Prod. 142, 538–547.

Hu, Z., 2021. De-coalizing rural China: a critical examination of the coal to clean heating project from a policy process perspective. Front. Energy Res. 9.

Hyndman, R., Athanasopoulos, G., Bergmeir, C., Caceres, G., Chhay, L., O'Hara-Wild, M., Petropoulos, F., Razbash, S., Wang, E., Yasmeen, F., 2022. Forecast: Forecasting Functions for Time Series and Linear Models (Manual).

Hyndman, R.J., Athanasopoulos, G., 2018. Forecasting: Principles and Practice. OTexts.

Hyndman, R.J., Khandakar, Y., 2008. Automatic time series forecasting: the forecast package for R. J. Stat. Software 26, 1–22. https://doi.org/10.18637/jss.v027.i03.

IEA, 2022. Tracking SDG7: the Energy Progress Report (Text/HTML). IEA, Paris.

Imai, K., Kim, I.S., 2021. On the use of two-way fixed effects regression models for causal inference with panel data. Polit. Anal. 29, 405–415.

Institute for Health Metrics and Evaluation (IHME), 2020. GBD results [WWW document]. Inst. Health metr. Evaluation. URL. https://www.healthdata.org/data-visualization/gbd-results. (Accessed 22 July 2022).

Jeuland, M., Pattanayak, S.K., Bluffstone, R., 2015. The economics of household air pollution. Annu. Rev. Resour. Econ. 7, 150710224125002.

Jiang, L., O'Neill, B.C., 2004. The energy transition in rural China. Int. J. Global Energy Issues 21, 2–26.

Kalli, R., Jena, P.R., Managi, S., 2022. Subsidized LPG scheme and the shift to cleaner household energy use: evidence from a tribal community of eastern India. Sustainability 14, 2450. https://doi.org/10.3390/su14042450.

Kim, K.-H., Jahan, S.A., Kabir, E., 2011. A review of diseases associated with household air pollution due to the use of biomass fuels. J. Hazard Mater. 192, 425–431.

Kuster, C., Rezgui, Y., Mourshed, M., 2017. Electrical load forecasting models: a critical systematic review. Sustain. Cities Soc. 35, 257–270. https://doi.org/10.1016/j.scs.2017.08.009.

Lewis, J.J., Pattanayak, S.K., 2012. Who adopts improved fuels and cookstoves? A systematic review. Environ. Health Perspect. 120, 637.

Li, J., Chen, C., Liu, H., 2019. Transition from non-commercial to commercial energy in rural China: insights from the accessibility and affordability. Energy Pol. 127, 392–403. https://doi.org/10.1016/j.enpol.2018.12.022.

Liao, H., Chen, T., Tang, X., Wu, J., 2019. Fuel choices for cooking in China: analysis based on multinomial logit model. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2019.03.302.

Ma, C., Liao, H., 2018. Income elasticity of cooking fuel substitution in rural China: evidence from population census data. J. Clean. Prod. 199, 1083–1091.
Ma, T., Zhang, S., Xiao, Y., Liu, X., Wang, M., Wu, K., Shen, G., Huang, C., Fang, Y.R., Xie, Y., 2023. Costs and health benefits of the rural energy transition to carbon neutrality in China. Nat. Commun. 14, 6101. https://doi.org/10.1038/s41467-023-41707-7.
Maina, Y.B., Dantama, U.Y., Kyari, B., 2017. Energy ladder: myth reality? An empirical study of the households in the North-east region of Nigeria. Int. J. Res. Publ. Res. J. Soc. Sci. Manag. 7, 82–89.
Masera, O.R., Saatkamp, B.D., Kammen, D.M., 2000. From linear fuel switching to multiple cooking strategies: a critique and alternative to the energy ladder model. World Dev. 28, 2083–2103.
Moritz, S., Bartz-Beielstein, T., 2017. imputeTS: Time Series Missing Value Imputation in R, vol. 9. R J, p. 207.
National Bureau of Statistics of China, 2024. National data [WWW Document]. URL. https://data.stats.gov.cn/easyquery.htm?cn=E0103, 3.1.24.
National Bureau of Statistics of China, 2016. China Energy Statistical Yearbook 2016. China Statistics Press.
National Bureau of Statistics of China, 1996. First-round China agricultural census [WWW Document]. URL. https://www.stats.gov.cn/sj/pcsj/nypc/dycnypc/index_16.html, 3.1.24.
Niu, S., Li, Z., Qiu, X., Dai, R., Wang, X., Qiang, W., Hong, Z., 2019. Measurement of effective energy consumption in China's rural household sector and policy implication. Energy Pol. 128, 553–564.
Paudel, U., Khatri, U., Pant, K.P., 2018. Understanding the determinants of household cooking fuel choice in Afghanistan: a multinomial logit estimation. Energy 156, 55–62.
Quinn, A.K., Bruce, N., Puzzolo, E., Dickinson, K., Sturke, R., Jack, D.W., Mehta, S., Shankar, A., Sherr, K., Rosenthal, J.P., 2018. An analysis of efforts to scale up clean household energy for cooking around the world. Energy Sustain. Dev. 46, 1–10.
Rehfuess, E., World Health Organization, 2006. Fuel for Life: Household Energy and Health. World Health Organization.
Rehfuess, E.A., Bruce, N.G., Smith, K.R., 2017. Solid Fuel Use: Health Effect.
Rhode, D., Madsen, D.B., Jeffrey Brantingham, P., Dargye, T., 2007. Yaks, yak dung, and prehistoric human habitation of the Tibetan Plateau. In: Developments in Quaternary Sciences, Late Quaternary Climate Change and Human Adaptation in Arid China. Elsevier, pp. 205–224. https://doi.org/10.1016/S1571-0866(07)09013-6.
Sánchez-Guevara, C., Fernández, A.S., Aja, A.H., 2015. Income, energy expenditure and housing in Madrid: retrofitting policy implications. Build. Res. Inf. 43, 737–749. https://doi.org/10.1080/09613218.2014.984573.
Shen, G., Xiong, R., Tian, Y., Luo, Z., Jiangtulu, B., Meng, W., Du, W., Meng, J., Chen, Yuanchen, Xue, B., Wang, B., Duan, Y., Duo, J., Fan, F., Huang, L., Ju, T., Liu, F., Li, S., Liu, X., Li, Y.Wangmo, Nan, Y., Pan, B., Pan, Y., Wang, L., Zeng, E., Zhan, C., Chen, Yilin, Shen, H., Cheng, H., Tao, S., 2022. Substantial transition to clean household energy mix in rural households in China. Natl. Sci. Rev., nwac050 https://doi.org/10.1093/nsr/nwac050.
Shi, X., Zheng, Y., Lei, Y., Xue, W., Yan, G., Liu, X., Cai, B., Tong, D., Wang, J., 2021. Air quality benefits of achieving carbon neutrality in China. Sci. Total Environ. 795, 148784 https://doi.org/10.1016/j.scitotenv.2021.148784.
Sinton, J.E., Smith, K.R., Peabody, J.W., Yaping, L., Xiliang, Z., Edwards, R., Quan, G., 2004. An assessment of programs to promote improved household stoves in China. Energy Sustain. Dev. 8, 33–52.
Station of Agricultural Ecology and Resource Conservation, 2019. Typical Rural Energy Model:Domestic Energy. China Agricultural Press.
Takama, T., Tsephel, S., Johnson, F.X., 2012. Evaluating the relative strength of product-specific factors in fuel switching and stove choice decisions in Ethiopia. A discrete choice model of household preferences for clean cooking alternatives. Energy Econ. 34, 1763–1773.
Tang, X., Liao, H., 2014. Energy poverty and solid fuels use in rural China: analysis based on national population census. Energy Sustain. Dev. 23, 122–129.
Tao, S., Ru, M.Y., Du, W., Zhu, X., Zhong, Q.R., Li, B.G., Shen, G.F., Pan, X.L., Meng, W.J., Chen, Y.L., Shen, H.Z., Lin, N., Su, S., Zhuo, S.J., Huang, T.B., Xu, Y., Yun, X., Liu, J. F., Wang, X.L., Liu, W.X., Cheng, H.F., Zhu, D.Q., 2018b. Quantifying the rural residential energy transition in China from 1992 to 2012 through a representative national survey. Nat. Energy 3, 567–573. https://doi.org/10.1038/s41560-018-0158-4.
van der Kroon, B., Brouwer, R., van Beukering, P.J.H., 2013. The energy ladder: theoretical myth or empirical truth? Results from a meta-analysis. Renew. Sustain. Energy Rev. 20, 504–513. https://doi.org/10.1016/j.rser.2012.11.045.
Villavicencio Calzadilla, P., Mauger, R., 2018. The UN's new sustainable development agenda and renewable energy: the challenge to reach SDG7 while achieving energy justice. J. Energy Nat. Resour. Law 36, 233–254. https://doi.org/10.1080/02646811.2017.1377951.
Wang, Q., Li, S., Li, R., 2018. Forecasting energy demand in China and India: using single-linear, hybrid-linear, and non-linear time series forecast techniques. Energy 161, 821–831. https://doi.org/10.1016/j.energy.2018.07.168.
Wang, R., Jiang, Z., 2017. Energy consumption in China's rural areas: a study based on the village energy survey. J. Clean. Prod. 143, 452–461.
Wang, X., Feng, Z., 1997. Rural household energy consumption in Yangzhong county of Jiangsu province in China. Energy 22, 1159–1162.
Wang, X., Li, K., Li, H., Bai, D., Liu, J., 2017. Research on China's rural household energy consumption–Household investigation of typical counties in 8 economic zones. Renew. Sustain. Energy Rev. 68, 28–32.
World Health Organization, 2016. Burning Opportunity: Clean Household Energy for Health, Sustainable Development, and Wellbeing of Women and Children.
Wu, S., Zheng, X., 2022. Revisit of household energy ladder - empirical evidence from a household survey in rural China. Chin. Econ. Q 22, 45–66. https://doi.org/10.13821/j.cnki.ceq.2022.01.03.
Wu, S., Zheng, X., Wei, C., 2017. Measurement of inequality using household energy consumption data in rural China. Nat. Energy 2, 795–803.
Wu, S., Zheng, X., You, C., Wei, C., 2019. Household energy consumption in rural China: historical development, present pattern and policy implication. J. Clean. Prod. 211, 981–991. https://doi.org/10.1016/j.jclepro.2018.11.265.
Yang, K., 2021. Power industry provides inexhaustible power for national rejuvenation [WWW Document]. China Power News Netw. URL. https://www.cpnn.com.cn/news/xxdlxt/202107/t20210714_1404937.html. (Accessed 14 July 2023).
Yao, C., Chen, C., Li, M., 2012. Analysis of rural residential energy consumption and corresponding carbon emissions in China. Energy Pol. 41, 445–450.
Zhang, L., Yang, Z., Chen, B., Chen, G., 2009. Rural energy in China: pattern and policy. Renew. Energy 34, 2813–2823.
Zhang, M., Guo, F., 2013. Analysis of rural residential commercial energy consumption in China. Energy 52, 222–229.
Zhang, X., Jin, Y., Dai, H., Xie, Y., Zhang, S., 2019. Health and economic benefits of cleaner residential heating in the Beijing–Tianjin–Hebei region in China. Energy Pol. 127, 165–178.
Zhang, X., Xu, K., He, M., Wang, J., 2022. A review on the rural household energy in China from 1990s—transition, regional heterogeneity, emissions, energy-saving, and policy. Front. Energy Res. 10.
Zhao, X., Ma, X., Chen, B., Shang, Y., Song, M., 2022. Challenges toward carbon neutrality in China: strategies and countermeasures. Resour. Conserv. Recycl. 176, 105959 https://doi.org/10.1016/j.resconrec.2021.105959.
Zheng, X.Meihui, 2022. Revisit of household energy ladder-empirical evidence from a household survey in rural China. Chin. Econ. Q 22, 45–66. https://doi.org/10.13821/j.cnki.ceq.2022.01.03.
Zheng, X., Wei, C., 2019. Household Energy Consumption in China: 2016 Report. Springer.
Zhou, Z., Wu, W., Chen, Q., Chen, S., 2008. Study on sustainable development of rural household energy in northern China. Renew. Sustain. Energy Rev. 12, 2227–2239.
Zhou, Z., Wu, W., Wang, X., Chen, Q., Wang, O., 2009. Analysis of changes in the structure of rural household energy consumption in northern China: a case study. Renew. Sustain. Energy Rev. 13, 187–193.