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Health implications of cooking energy transition: Evidence from rural China

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Abstract

The transition towards advanced residential energy sources is a pressing priority for many countries. Despite this, solid fuels remain the dominant form of cooking energy for rural households in developing countries. This study investigates the physical and mental health impacts of cooking energy choices by using endogenous switching models to address selection bias associated with cooking energy adoption and to distinguish the health impacts of different types of cooking energy. Using country-representative household survey data from rural China, our results indicate that adopting advanced forms of energy, not only enhances physical health in terms of reducing the rates of chronic diseases but also improves mental health. We further delve into the heterogenous impacts of advanced energy adoption across different groups and find that women, old adults, and economically disadvantaged groups are more likely to experience greater mental health benefits compared to their counterparts, while the opposite results are observed for the physical health. Additionally, we differentiate the health impacts by distinguishing between various energy types. This study provides insights for policy making aimed at improving public health and promoting health equality, contributing to efforts towards achieving sustainable development goals by prioritizing clean and efficient residential energy solutions.

1. Introduction

Globally, approximately three billion people still rely on solid fuels (e.g. coal and biomass) for cooking (WHO 2021). The combustion of solid fuels produces indoor air pollution comprising particulate matter and nitrogen dioxide, which harms human health (Goldemberg *et al* 2018, Buonocore *et al* 2021). Women and children are particularly affected, with increasing incidence of respiratory disease, tuberculosis, and eye disease (Balmes 2019). Indoor air pollution ranks third in terms in global disease burden (Lim *et al* 2012). The World Health Organization (WHO) highlights that the inefficient use of solid fuels and kerosene for cooking causes 3.8 million premature deaths annually worldwide (WHO 2020). Despite the low direct costs of solid energy, their overall costs may exceed those of alternatives when accounting for opportunity costs of energy collection and associated health costs (González-Eguino 2015).

The transition towards advanced residential energy (e.g. gas and electricity) is a global priority, aligning with the 2030 Agenda for Sustainable Development Goals (SDGs) to ensure "access to cheap, reliable and sustainable modern energy". China is a key player in this transition, as household energy use largely contributes to air pollution and greenhouse gas emissions (Tao *et al* 2018, Shen et al 2019). The use of solid energy in China, often under poor combustion conditions without end-of-pipe control devices, leads to high levels of pollution (Meng et al 2019, Lu et al 2022). The residential sector accounts for 27% of primary PM2.5 and 51% of black carbon emissions, with 80% from rural areas (Zhu et al 2019). In response, the Chinese government is promoting energy transition to support green development and a low-carbon economy (Yu et al 2020, Wu et al 2024). Efforts in the rural sector focus on adopting advanced forms of energy. As a result, China achieved full electrification in 2015 (He et al 2018), and increased renewable energy use in rural areas (Li et al 2019).

However, biomass energy still predominates residential consumption in rural China, despite of the energy source shift since 1992 (Han et al 2018, Tao et al 2018, Ma et al 2022). Biomass energy consumption under current trends is projected to still account for 35% of total rural energy use by 2060 compared to 63% in 2014 (Ma et al 2023). Due to the lack of large-scale records about rural residential energy consumption, existing literature on its impacts remains uncertain (Tao et al 2018), and the relationship between cooking energy choice and health is not yet fully understood.

Using country-representative household survey data from rural China, we investigate the impacts of cooking energy choices on individual health. This study makes three key contributions to the literature. Firstly, while previous studies have primarily focused on the physical health impacts of solid energy use, the mental health effects remain underexplored. Transitioning to clean energy can increase energy efficiency, reducing the time spent collecting biomass and freeing up time for productive activities or leisure (Dinkelman 2011, Thiam 2017, Tonn et al 2021). Moreover, indoor air pollution from solid energy combustion has been linked to reduced life satisfaction and increased mental illness (Awaworyi Churchill et al 2020, Nie et al 2021). While recent studies have explored the mental health benefits of energy transition (Cong et al 2021, Liu et al 2022, Ma et al 2022), they mainly focus on adults, especially the elderly (Liu et al 2018, 2020, Qiu et al 2019, Luo et al 2021). Our study extends the literature by investigating both physical and mental health impacts of energy transition across a broader demographic, including younger populations.

Secondly, previous studies on indoor air pollution and health outcomes often rely on controlled experiments with limited sample sizes or geographic coverage (Baumgartner et al 2011, Madureira et al 2016, Cole-Hunter et al 2021, Hou et al 2022, Zhang et al 2022). Our study addresses these limitations by using country-representative survey data that covers all age groups, enhancing generalizability. This approach offers insights into the heterogeneous impacts of adopting advanced cooking energy across demographic groups (i.e. gender, age, and economic conditions), addressing concerns about external validity, particularly in rural areas (Tao et al 2018).

Thirdly, we provide a more nuanced analysis by distinguishing between the effects of biomass and coal, which are often grouped together in previous studies (Luo et al 2021, Maji et al 2021). We address potential selection biases related to household energy choices arising from omitted and unobserved confounders. Furthermore, we differentiate the impacts of transitioning to different forms of clean energy. This approach provides clearer guidance for policy interventions targeting priority groups, supporting health improvement and reducing health inequality, which is crucial for an ageing country aiming for social inclusion.

2. Data and methods

2.1. Data

This study employs household survey data from the China Family Panel Studies (CFPS) conducted by the Peking University. It is a large-scale, country-representative survey that captures a wide range of information on socioeconomic status, demography, health and behavior at both individual (adults and children) and household levels. As health is multidimensional, this study considers a number of standard physical and mental health indicators, following Böhme et al (2015) and Pan and Dong (2020). For physical health, chronic disease is represented by a dummy variable set to be one if an individual is diagnosed by a doctor in the last six months, and zero otherwise. For mental health, we construct an indicator of symptoms of poor mental health (SPM) using questions from CFPS data. Positive mental health questions, including "I have a happy life" and "I feel happy", are scored as follows: 1 = Most of the time; 2 = Often; 3 = Sometimes; 4 = Never; Negative mental health questions, including "I am in a low spirit", "I find it difficult to do anything", "I cannot sleep well", "I feel lonely", "I feel sad", and "I feel that I cannot continue with my life", are scored as: 1 = Never, 2 = Sometimes; 3 = Often, 4 = Most of the time. We then sum the values of all answers to obtain the SPM score, which ranges from 8 (best) to 32 (worst). Additionally, we construct the Center for Epidemiologic Studies Depression Scale (CES-D) in a six-item scale as an alternative measure of SPM, following Kessler et al (2002) and Hua et al (2022). The key variable of interest is the primary energy type used for cooking, categorized into solid fuel (i.e. coal and biomass) and the advanced forms of energy (i.e. natural gas, electricity, and solar power, and liquefied petroleum gas (LPG)). Energy stacking theory suggests that as income increases, residents tend to use a mixed of fuel types rather than fully transitioning away from lower-level energy, a trend supported by previous studies (Hou *et al* 2022, Ma *et al* 2022). We focus on the primary cooking fuel, defined as the main source used for stir-frying when respondents report using multiple fuel types. Despite the growing popularity of electric appliances for steaming or boiling, stir-frying—a common cooking method—still heavily relies on solid fuels burned in primitive stoves. This makes cooking energy a major source of indoor pollution (Liao *et al* 2016).

We control for additional variables that may influence health outcomes, following existing literature (Li *et al* 2021, Maji *et al* 2021, Hou *et al* 2022, Ma *et al* 2022). Smoking is among the top three contributors to the global burden of disease (Lim *et al* 2012) and a major health risky behavior (Böckerman *et al* 2018). We also control for adequate sleep, a key factor for mental health. To account for socioeconomic and demographic influences on energy choice and health outcomes, we include variables such as the respondent's gender, age, educational level, household size, and income level. These variables are crucial as they can affect indoor air pollution via energy choice (Li *et al* 2021). We further control for heating energy expenditure, since rural households in colder regions often rely on traditional heating methods that produce smoke and other pollutants. Finally, we control for regional differences by incorporating regional dummy variables to capture potential unobserved regional heterogeneity affecting health outcomes. Table 1 reports the definitions and summary statistics of the variables used in this study.

2.2. Methods

We aim to estimate the impacts of adopting advanced cooking energy on individual health in rural China. The decision to adopt advanced energy and its health effects are separate but linked. While the literature has explored energy adoption decisions (Gebreegziabher *et al* 2012, Gould and Urpelainen 2018, Kar *et al* 2019, Troncoso *et al* 2019), unobserved heterogeneity in adoption decisions is often overlooked, and the heterogeneous health effects of adopting advanced energy remain understudied. Considering unobserved heterogeneity is crucial in impact evaluation of technological adoption (Wagstaff 2011). We use endogenous switching models to account for systematic differences between households adopting advanced cooking energy and those using solid energy.

Here we outline an endogenous switching regression (ESR) model (Lokshin and Sajaia 2004, Di Falco *et al* 2011), which can be adapted to specific cases with a binary dependent variable in the form of an endogenous switching probit (ESP) model (Lokshin and Glinskaya 2009, Wagstaff 2011).

$$\begin{aligned} &G_{it} = 1 \text{ if } Z'_{it}\gamma + u_{it} > 0 \\ &G_{it} = 0 \text{ if } Z'_{it}\gamma + u_{it} \leqslant 0 \\ &H_{it,1} = X'_{it,1}\delta_1 + \varepsilon_{it,1} \text{ } if \text{ } G_{it} = 1 \\ &H_{it,0} = X'_{it,0}\delta_0 + \varepsilon_{it,0} \text{ } if \text{ } G_{it} = 0 \end{aligned} \quad (1)$$

where $H_{it,1}$ and $H_{it,0}$ are the observed health outcomes (H_{it}) of adopting advanced forms of cooking energy ($G_{it} = 1$) and of nonadopting ($G_{it} = 0$), respectively. Z'_{it} represents a vector of variables determining an individual whether or not using the advanced forms of cooking energy. $X'_{it,1}$ and $X'_{it,0}$ are the vector of variables that may impact the health outcomes, $H_{it,1}$ and $H_{it,0}$, respectively. The model assumes that the error terms—u_{it},$\varepsilon_{it,1}$, and $\varepsilon_{it,0}$ have a joint normal distribution with zero mean and the correlation matrix for each i, where ρ_0 is the correlation between $\varepsilon_{it,0}$ and μ_{it}, ρ_1 is the correlation between $\varepsilon_{it,1}$ and μ_{it}, and ρ_{10} is the correlation between $\varepsilon_{it,1}$ and $\varepsilon_{it,0}$. γ, δ_1 and δ_0 are column vectors of parameters to be estimated.

The above model can be adapted by introducing latent variables in the primary equations to accommodate specific cases with a binary dependent variable as follows:

$$\begin{aligned} &H_{it,1} = I\left(H^*_{it,1} > 0\right) = I\left(X'_{it,1}\delta_1 + \varepsilon_{it,1} > 0\right) \text{ } if \text{ } G_{it} = 1 \\ &H_{it,0} = I\left(H^*_{it,0} > 0\right) = I\left(X'_{it,0}\delta_0 + \varepsilon_{it,0} > 0\right) \text{ } if \text{ } G_{it} = 0 \end{aligned} \quad (2)$$

where $H^*_{it,1}$ and $H^*_{it,0}$ are latent variables that affect the observed health outcomes of adopting advanced forms of cooking energy ($H_{it,1}$) and of using solid fuels—being a nonadopter ($H_{it,0}$), in terms of whether having worse mental health or contracting chronic diseases. ESR and ESP models provide efficient estimates by using full information maximum likelihood (Lokshin and Sajaia 2004, 2011).

To address potential self-selection issue in adopting advanced energy, endogenous switching models require at least one instrumental variable (IV) in the selection equations for identification. We use whether a household engage in agri-forest production activities as the IV. Households with higher on-farm income tend to use more biomass energy (Jiang *et al* 2020, Gao and Yu 2024) and engaging in agri-forest production activities is likely to be correlated with the household's probability of using solid energy. The IV must meet two conditions: (1) the relevance condition meaning that the IV is correlated with the households' energy adoption decision, and (2) the exclusion restriction condition meaning that the IV has no direct effects on individual health condition except through its effect on households' use behavior of cooking fuels.

To verify instrument admissibility, we follow Lin *et al* (2022) by running two separate fixed effect models—one for the selection equation for cooking fuel decision and the other for the outcome equation

Table 1. Definitions and summary statistics of variables used in this study.

Variables	Description	Mean	S.D.	Min	Max
Health outcomes					
SPM	Poor mental health, the lower, the better.	13.665	4.127	8	32
Chronic disease	1 if an individual respondent had chronic diseases in the last six months, 0 otherwise	0.167	0.373	0	1
Cooking energy choice					
Adopter	1 if the household uses advanced energy for cooking, 0 otherwise	0.515	0.5	0	1
Individual- and household-level characteristics					
Gender	1 if an individual respondent is male, 0 female	0.504	0.5	0	1
Age	Age of individual respondent	45.622	18.612	9	100
Sleeping hour	Sleeping hours of an individual respondent per day	7.957	1.488	4	12
Individual income level	Individual income level (CNY)[1]	5961.94	15 314.567	0	100 000
Educational level	1 if an individual respondent is literate, 0 otherwise	0.677	0.468	0	1
Household size	Number of persons in a household	4.54	2.183	1	21
Smoking year	Years of smoking by an individual respondent	1.128	6.246	0	70
Heating	1 if the household pays heating fee, 0 otherwise	0.076	0.265	0	1
Agri-forest work	1 if an individual respondent is employed in the agri-forest sector, 0 otherwise	0.974	0.16	0	1
Alternative health outcomes					
Medical expenditure	Medical expenditure of an individual respondent in the last 12 months (CNY)	5874.796	18 103.231	0	1200 000
CES-D score	Center for Epidemiologic Studies Depression Scale, the lower, the better.	9.523	3.24	6	24
Respiratory disease	1 if an individual respondent had respiratory diseases in the last six months, 0 otherwise	0.012	0.111	0	1
Cardiovascular disease	1 if an individual respondent had cardiovascular disease in the last six months, 0 otherwise	0.062	0.24	0	1
Digestive disease	1 if an individual respondent had cardiovascular disease in the last six months, 0 otherwise	0.029	0.167	0	1

Note: 1 USD = 6.94 CNY on 6 March 2023.

of effects of cooking fuel decision on individual health conditions. The estimation in Table A1 supports the conditions (1) and (2) discussed above. We also perform a falsification test following Di Falco *et al* (2011), examining whether the IV affects the treatment variable but does not affect the outcome variable if the individuals are not in the treatment group. Table A2 supports the validity of IV in our study.

The results from the endogenous switching models are used to construct the actual and the counterfactual scenarios to estimate the average treatment effect of treated (ATT) and average treatment effect of untreated (ATU) of adopting advanced forms of energy. ATT is the difference between the average outcomes observed for the adopters and the average outcomes they would have experienced had they instead not adopted the advanced cooking energy, while the ATU is the treatment would have had for the nonadopters had they adopted the advanced cooking energy (Wood and Donnell 2017). The estimates of ATT and ATU for the ESR model are derived as follows:

$$\tau_{\mathrm{ESR}}^{\mathrm{ATT}} = \frac{1}{N_T}\sum_{i:G_i=1}^{N_T}\left\{E\left(H_{it,1}|G_{it}=1,X_{it,1}\right)-E\left(H_{it,0}|G_{it}=1,X_{it,1}\right)\right\}$$
$$= \frac{1}{N_T}\sum_{i:G_{it}=1}^{N_T}\left\{X'_{it,1}\left(\delta_1-\delta_0\right)+\frac{\left(\sigma_1\rho_1-\sigma_0\rho_0\right)f\left(Z'_{it,1}\gamma\right)}{F\left(Z'_{it,1}\gamma\right)}\right\} \tag{3}$$

$$\tau_{\mathrm{ESR}}^{\mathrm{ATU}} = \frac{1}{N_{NT}}\sum_{i:G_{it}=0}^{N_{NT}}\left\{E\left(H_{it,1}|G_{it}=0,X_{it,0}\right)-E\left(H_{it,0}|G_{it}=0,X_{it,0}\right)\right\}$$
$$= \frac{1}{N_{NT}}\sum_{i:G_{it}=0}^{N_{NT}}\left\{X'_{it,0}\left(\delta_1-\delta_0\right)+\frac{\left(\sigma_1\rho_1-\sigma_0\rho_0\right)f\left(Z'_{it,0}\gamma\right)}{1-F\left(Z'_{it,0}\gamma\right)}\right\} \tag{4}$$

where $N_T=\sum_{i=1}^{N}G_{it}$ is the number of treated individuals and $N_{NT}=N-\sum_{i=1}^{N}G_{it}$ is the number of untreated individuals. Similarly, the ATT and ATU for the ESP model are calculated as follows:

$$\tau_{\mathrm{ESP}}^{\mathrm{ATT}} = \frac{1}{N_T}\sum_{i:G_{it}=1}^{N_T}\left\{\Pr\left(H_{it,1}|G_{it}=1,X_{it,1}\right)-\Pr\left(H_{it,0}|G_{it}=1,X_{it,1}\right)\right\}$$
$$= \frac{1}{N_T}\sum_{i:G_{it}=1}^{N_T}\left\{\frac{\Phi_2\left(X'_{it,1}\delta_1,Z'_{it,1}\gamma,\rho_1\right)-\Phi_2\left(X'_{it,1}\delta_0,Z'_{it,1}\gamma,\rho_0\right)}{F\left(Z'_{it,1}\gamma\right)}\right\} \tag{5}$$

$$\tau_{\mathrm{ESP}}^{\mathrm{ATU}} = \frac{1}{N_{NT}}\sum_{i:G_{it}=0}^{N_{NT}}\left\{\Pr\left(H_{it,1}|G_{it}=0,X_{it,0}\right)-\Pr\left(H_{it,0}|G_{it}=0,X_{it,0}\right)\right\}$$
$$= \frac{1}{N_{NT}}\sum_{i:G_{it}=0}^{N_{NT}}\left\{\frac{\Phi_2\left(X'_{it,0}\delta_1,-Z'_{it,0}\gamma,-\rho_1\right)-\Phi_2\left(X'_{it,0}\delta_2,-Z'_{it,0}\gamma,-\rho_0\right)}{F\left(-Z'_{it,0}\gamma\right)}\right\}. \tag{6}$$

3. Results and discussion

3.1. Descriptive analysis

Our samples reveal a clear transition in residential energy consumption in rural China from 2016 to 2018 (Figure 1(a)). The proportion of households using solid energy (coal and biomass) for cooking decreased from 52.20% in 2016 to 43.60% in 2018. Despite this decline, biomass energy, such as firewood and crop residue, remained the primary source, with 38.20% of households still using it in 2018, down from 45.10% in 2016. Nearly full electricity coverage was achieved by 2018, but only 23.20% of sample households used electricity for cooking. The percentage of households using gas/LPG for cooking increased from 26.70% in 2016 to nearly one-third in 2018. The use of solar and biogas energy sources remained limited during the study period. Additionally, biomass energy usage decreased markedly with rising income, from 51.30% in the poorest group to 17% in the wealthiest group (Figure 1(b)). Conversely, gas/LPG consumption increased with income, ranging from 20% in the poorest group to 59.90% in the richest group. Coal and electricity consumption did not display a pronounced relationship with income. Even among the wealthiest households, solid fuels were still used, although to a much less extent compared to the poorest group.

There are significant differences between adopters and nonadopters of advanced cooking energy (Table A3). Adopters are less likely to suffer from chronic diseases, have better mental health, compared to non-adopters. They also differ significantly in age, sleeping hours, income, educational level, household size, smoking years and heating expenditure. While these results highlight differences between adopters and nonadopters, they do not allow for inferences about the impacts of adopting advanced cooking energy on health status, which will be addressed using econometric method.

3.2. Mental and physical health impacts of cooking energy choices

3.2.1. Determinants and health impacts of advanced cooking energy choices

Using endogenous switching models, we estimate the impacts of cooking energy choices on mental health and physical health (Table 2), with standard errors clustered at the individual level to account for possible

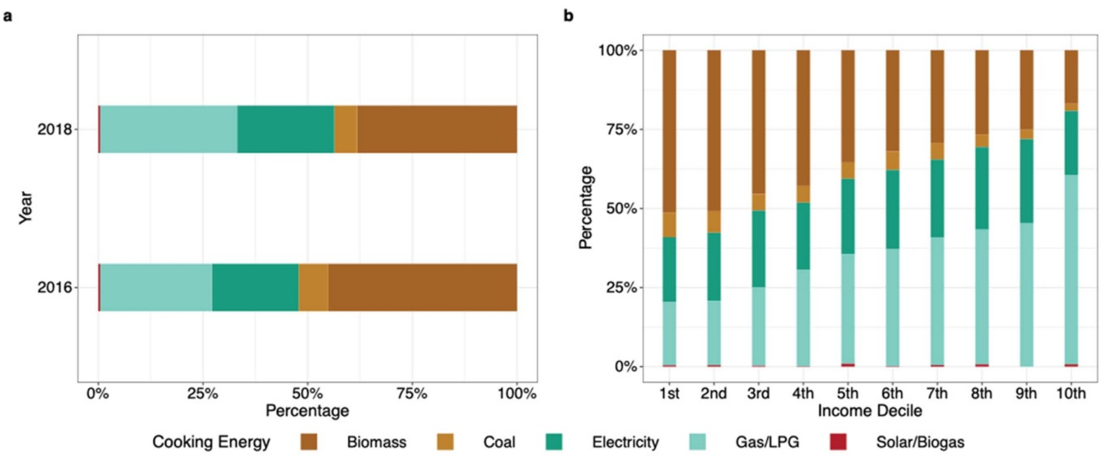

Figure 1. Frequency of types of energy used for cooking by households in rural China. (a) Types of energy used for households cooking in 2016 and 2018. (b) Types of energy used across income deciles in 2018.

Table 2. The impacts of adopting advanced forms of energy on individual health.

	Mental health (SPM)			Physical health (chronic disease)		
Variable	Selection (1)	Adopters (2)	Nonadopters (3)	Selection (4)	Adopters (5)	Nonadopters (6)
Gender	-0.092^{***}	-0.778^{***}	-0.986^{***}	-0.112^{***}	-0.215^{***}	-0.190^{***}
	(0.020)	(0.081)	(0.079)	(0.021)	(0.037)	(0.024)
Age	-0.001	0.019^{***}	0.038^{***}	-0.0001	0.027^{***}	0.015^{***}
	(0.001)	(0.002)	(0.002)	(0.001)	(0.001)	(0.002)
Sleeping hour	0.004	-0.229^{***}	-0.228^{***}	0.002	-0.028^{**}	-0.003
	(0.006)	(0.030)	(0.028)	(0.006)	(0.011)	(0.007)
Individual income level (log)	0.009^{***}	0.004	0.007	0.009^{***}	-0.006^{**}	0.004^{**}
	(0.001)	(0.004)	(0.004)	(0.001)	(0.002)	(0.002)
Educational level	0.312^{***}	-0.580^{***}	-0.425^{***}	0.341^{***}	0.092	0.206^{***}
	(0.022)	(0.105)	(0.088)	(0.024)	(0.070)	(0.031)
Household size	0.001	-0.085^{***}	-0.101^{***}	0.002	-0.007	-0.010^{*}
	(0.004)	(0.019)	(0.017)	(0.004)	(0.008)	(0.005)
Smoking year	0.001	0.003	-0.008	0.001	0.00002	0.002
	(0.001)	(0.006)	(0.006)	(0.001)	(0.002)	(0.002)
Heating	0.183^{***}	0.245	0.227	0.176^{***}	0.131^{**}	0.172^{***}
	(0.033)	(0.150)	(0.152)	(0.034)	(0.063)	(0.040)
Agri-forest work	-0.167^{***}			-0.161^{***}		
	(0.053)			(0.050)		
Year dummy	Yes	Yes	Yes	Yes	Yes	Yes
Region dummy	Yes	Yes	Yes	Yes	Yes	Yes
Constant	Yes	Yes	Yes	Yes	Yes	Yes
Observations		25 101			23 985	
Log likelihood		−85 990.738			−25 165.38	
σ		3.788^{***}	4.044^{***}			
		(0.037)	(0.033)			
LnS		1.339^{***}	1.393^{***}			
		(0.009)	(0.007)			
ρ		-0.013	0.090^{***}		0.146	1.540^{***}
		(0.019)	(0.025)		(0.276)	(0.266)
Wald test		$\chi^2(2) = 13.62$			$\chi^2(2) = 34.69$	

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors in parentheses are clustered at the individual level.

serial dependence in the error term (Semykina and Wooldridge 2018). Results of mental health impacts are reported in Columns 1–3 based on ESR model, while Columns 4–6 show the estimation of physical health based on ESP model. The coefficients of covariance (σ) are significant, which indicates that the null hypothesis of selection bias being absent is rejected. The IV of working in the agri-forest sector appears to have a significant and negative impact on the adoption of advanced cooking energy. This is considered reasonable, given that being involved in the agricultural or forestry sector would likely provide

Table 3. Treatment effects of adopting advanced energy on individual health.

	Mean outcomes			
	Adopters	Counterfactuals	ATT	Changes
SPM	13.194 (0.008)	14.238 (0.010)	−1.044*** (0.003)	−7.33%
Chronic disease	0.146 (0.001)	0.843 (0.001)	−0.696*** (0.001)	−82.62%
	Nonadopters	Counterfactuals	ATU	Changes
SPM	13.575 (0.008)	13.955 (0.010)	−0.380*** (0.003)	−2.72%
Chronic disease	0.117 (0.001)	0.173 (0.001)	−0.056*** (0.0003)	−32.22%

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors in parentheses are reported by t-test.

easy access to straw, firewood or other source of biomass. A Wald test rejects the null hypothesis that the primary and selection equations are independent of each other, indicating the plausibility of using the endogenous switching models.

Columns 1 and 4 present the determinants of advanced cooking energy choices in rural households. Income and educational levels of individuals, and heating used by individuals play positive roles in the adoption of advanced energy, consistent with the empirical findings from other countries (Mobarak *et al* 2012, Beyene and Koch 2013, Beltramo *et al* 2015, Zhu *et al* 2022). Additionally, female residents are more inclined to adopt the advanced cooking energy. Column 4 in Table 2 reports factors affecting cooking energy choices based on the ESP model, with results that are mostly similar to those derived from the ESR model (Column 1).

For the mental health impacts (Columns 2 and 3), a noteworthy finding is that females tend to experience a significantly higher prevalence of mental illness, consistent with previous findings (Liu *et al* 2022), highlighting the importance of addressing mental health concerns specific to women. Additionally, sleeping hours, educational level and household size of the residents have negative and significant effects on individual SPM scores for both groups, while age of residents has positive and significant effects. Regarding the impacts of advance cooking energy on physical health (Columns 5 and 6), the results show that respondent's age has significant and positive impacts on the incidence of chronic diseases, suggesting that the elderly in rural areas are most likely to contract chronic diseases. For those adopting advanced energy, adequate sleep reduces the likelihood of chronic diseases, while household size negatively impacts the incidence of chronic diseases among nonadopters. Individual income levels exhibit mixed effects on physical health: it has a significant and negative impact on chronic disease for advanced energy users, whereas it has a significant and positive impact for those using solid fuels. Moreover, women are more likely to suffer from chronic diseases, and individuals with access to heating have a higher incidence of chronic diseases.

3.2.2. Treatment effects of cooking energy adoption choice on individual health

Using coefficients from the ESR model and ESP models, we compute the treatment effects of adopting advanced cooking energy on individual health (Table 3). The ATT result of SPM shows that individuals using advanced forms of cooking energy have a 7.33 percentage points lower score in mental health than their counterfactuals, suggesting improved mental health. This improvement may result from the time saved in biomass collection for other productive activities or leisure (Dinkelman 2011, Thiam 2017, Tonn *et al* 2021). The ATU estimate indicates that SPM for nonadopters could have decreased by 2.72% if they switched to advance energy.

For chronic diseases, the ATT result shows that adopters of advanced cooking energy have an 82.62 percentage points lower probability of contracting chronic diseases compared to nonadopters. This suggests a significant and positive impact on health, likely due to better indoor air quality (Lacey *et al* 2017). The ATU result shows that the probability of contracting chronic diseases among nonadopters would have decreased by 32.22 percentage points if they switched to advanced energy.

3.3. Robustness checks

We conduct additional checks to ensure the robustness of our main estimations. Firstly, we estimate the impacts of cooking energy choices on various health outcomes (Table A4), including medical expenditure for overall health in the last 12 months, CES-D score and severe SPM for mental health, and physical health (digestive disease, respiratory disease, and cardiovascular disease). The estimation result shows that adopting advanced cooking energy reduces medical expenditure, suggesting that it has a positive impact on individuals' overall health. For mental health, we use the CES-D score, showing that the individuals

Table 4. Treatment effects of adopting advanced energy on individual health across socio-economic groups.

Category		Mean outcomes			
		Adopters	Counterfactuals	ATT	Changes
SPM	*Panel A: age group*				
	0–15	12.554 (0.030)	12.893 (0.031)	−0.339*** (0.005)	−2.63%
	16–29	12.572 (0.016)	13.260 (0.016)	−0.689*** (0.004)	−5.20%
	30–44	12.979 (0.016)	13.896 (0.016)	−0.917*** (0.004)	−6.60%
	45–59	13.380 (0.013)	14.562 (0.013)	−1.182*** (0.003)	−8.12%
	Over 60	13.801 (0.017)	15.220 (0.018)	−1.419*** (0.005)	−9.33%
	Panel B: gender group				
	Male	12.778 (0.010)	13.729 (0.012)	−0.952*** (0.005)	−6.93%
	Female	13.614 (0.011)	14.750 (0.012)	−1.136*** (0.004)	−7.70%
	Panel C: income group				
	Q1	13.281 (0.022)	14.364 (0.026)	−1.084*** (0.009)	−7.55%
	Q2	13.211 (0.017)	14.264 (0.021)	−1.053*** (0.007)	−7.38%
	Q3	13.148 (0.015)	14.177 (0.018)	−1.029*** (0.006)	−7.26%
	Q4	13.175 (0.015)	14.201 (0.018)	−1.026*** (0.006)	−7.22%
Chronic disease	*Panel A: age group*				
	0–15		No observations		
	16–29	0.041 (0.0004)	0.699 (0.001)	−0.658*** (0.001)	−94.14%
	30–44	0.088 (0.001)	0.810 (0.001)	−0.723*** (0.001)	−89.21%
	45–59	0.167 (0.001)	0.901 (0.001)	−0.734*** (0.0004)	−81.44%
	Over 60	0.293 (0.002)	0.960 (0.0005)	−0.666*** (0.001)	−69.40%
	Panel B: gender group				
	Male	0.127 (0.001)	0.822 (0.002)	−0.695*** (0.001)	−84.58%
	Female	0.167 (0.002)	0.864 (0.001)	−0.697*** (0.001)	−80.74%
	Panel C: income group				
	Q1	0.169 (0.003)	0.857 (0.003)	−0.688*** (0.001)	−80.27%
	Q2	0.150 (0.002)	0.847 (0.002)	−0.696*** (0.001)	−82.17%
	Q3	0.140 (0.002)	0.837 (0.002)	−0.697*** (0.001)	−83.28%
	Q4	0.137 (0.002)	0.836 (0.002)	−0.699*** (0.001)	−83.67%

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors in parentheses are reported by t-test. Q1, Q2, Q3 and Q4 represent 1st quantile, 2nd quantile, 3rd quantile and 4th quantile, respectively.

using advanced cooking energy have better mental health (2.79 percentage points lower). This ATT estimation is slightly lower than the SPM score due to the CES-D focusing solely on depression. We also define severe SPM as a score above 16, following Kessler *et al* (2002), Prochaska *et al* (2012), and Hua *et al* (2022), and find that advanced energy users have a lower likelihood of severe mental illness. We further use the dummy variables of digestive disease, respiratory disease, and cardiovascular disease to study the impacts of cooking energy choices on the specific chronic diseases. The results remain robust.

Secondly, we use multinomial ESR to estimate the impact of individual advanced cooking energy on SPM (Table A5). The results show negative and significant impacts on SPM for natural gas/LPG and electricity, indicating that individuals who adopt these energies are likely to benefit more in mental health than their counterfactuals. Individuals adopting natural gas/LPG gain the highest benefit, followed by electricity consumers. These findings are consistent with our main results.

Thirdly, we estimate multinomial endogenous treatment effects (METE) of individual advanced cooking energy type on chronic disease, following Khonje *et al* (2018) to accommodate that the variable of chronic disease is a binary outcome. The METE results (Table A6) show that the adoption of natural gas/LPG and electricity significantly reduces the likelihood of contracting chronic diseases. These findings confirm the robustness of the main results.

3.4. Heterogenous effects across socio-economic groups and energy types

Previous studies indicate that health impacts vary among population groups (Ren *et al* 2019). Women, who are mainly responsible for cooking, are more exposed to indoor air pollution, resulting in elevated blood pressure and cardiovascular events (Baumgartner *et al* 2011, Madureira *et al* 2016). Rural elderly are vulnerable to environmental pollution (Liu *et al* 2018, 2020, Qiu *et al* 2019), with growing concerns regarding their health. Thus, switching to non-solid energy is expected to benefit women and the elderly more. Our results confirm that adopting advanced fuels improves health, with varying benefits across groups (Table 4), with women having 0.77 percentage points greater improvement in mental health than men.

Table 5. Treatment effects of energy transition across energy types.

	Mean outcomes			
	Cooking energy adopters	Counterfactuals	Treatment effects	Changes
Panel A: energy transition from solid fuels to natural gas/LPG				
SPM	13.054	14.115	−1.061***	−7.51%
	(0.011)	(0.014)	(0.004)	
Chronic disease	0.142	0.836	−0.694***	−82.98%
	(0.001)	(0.001)	(0.001)	
Panel B: energy transition from solid fuels to electricity				
SPM	13.346	14.369	−1.023***	−7.12%
	(0.013)	(0.015)	(0.005)	
Chronic disease	0.150	0.849	−0.699***	−82.29%
	(0.001)	(0.002)	(0.001)	
Panel C: energy transition from solid fuels to solar power/biogas				
SPM	13.214	14.274	−1.060***	−7.42%
	(0.075)	(0.092)	(0.029)	
Chronic disease	0.159	0.849	−0.690***	−81.24%
	(0.009)	(0.010)	(0.005)	
Panel D: energy transition from biomass to advanced energy				
SPM	13.574	13.959	−0.385***	−2.76%
	(0.009)	(0.010)	(0.003)	
Chronic disease	0.118	0.174	−0.056***	−32.19%
	(0.001)	(0.001)	(0.0003)	
Panel E: energy transition from coal to advanced energy				
SPM	13.579	13.926	−0.347***	−2.49%
	(0.009)	(0.010)	(0.003)	
Chronic disease	0.113	0.167	−0.054***	−32.43%
	(0.002)	(0.003)	(0.001)	

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors in parentheses are reported by t-test.

For age groups, adults over 60 benefit the most in mental health from adopting advanced cooking fuels, while they see fewer advantages in mitigating chronic diseases. This disparity might be attributed to the fact that the elderly have potentially been living with chronic conditions for an extended period of time, making it more challenging to eliminate or significantly reduce these ailments. Nevertheless, energy transition remains crucial for the elderly, especially in rapidly aging China, where mental illness and chronic diseases are rising (Li and Lin 2016, Liu *et al* 2018). Policies targeting the elderly for cooking energy transition could yield significant health and welfare benefits, and reduce public healthcare expenditures for the country.

We also explore how different economic groups are impacted from shifting to advanced energy. The results illustrate that all population are likely to benefit from the transition, with the poorest experiencing the greatest mental health improvements (0.33 percentage points higher than the wealthiest). This indicates that adopting advanced energy can reduce health inequality. This has significant policy implications, as reducing health inequality aligns with the health and welfare goals outlined in the SDGs and contributes to the China's pursuit of common prosperity.

We further differentiate the health impacts of energy transition (Table 5), indicating that rural residents benefit the most in both mental and physical health from shifting to natural gas/LPG. Rural residents transitioning to electricity experience greater reduction in chronic disease likelihood than those transitioning to solar power/biogas, while opposite results are observed in the mental health. We further explore the health impacts of energy transition by distinguishing between the effects of biomass and coal. Rural individuals switching from biomass see a 0.27% improvement in mental health, while shifting from coal provides a greater reduction in chronic disease risk. These suggest that energy transition strategies should be tailored to improve both mental and physical health.

4. Conclusion and policy implications

This study investigates the impact of cooking fuel choices on individual mental and physical health by using endogenous switching models and representative household survey data from China. We find that transitioning to advanced cooking energy improves rural residents' mental and physical health. These findings suggest that promoting energy transition can enhance public health overall. Efforts to ensure the part of rural households that still use solid fuels to adopt advanced energy forms would improve societal welfare and contribute to the national goal of common prosperity.

Our findings reveal varying health improvement across demographic groups, with rural elderly benefiting most from mental health improvement due to energy transition. Given China's rapidly aging population and the large numbers of left-behind elderly in rural areas, addressing their mental health is increasingly urgent. The energy transition presents a key opportunity to enhance their well-being, and targeted incentives, such as advanced stove replacement programs or clean energy subsidies, could accelerate this transition and foster a more inclusive society. These health benefits could be even more pronounced as the pace of population aging continues to increase. Additionally, younger individuals could gain significant benefits, particularly by reducing chronic disease risks and preventing early onset. The focus on chronic diseases in the elderly has often overlooked rising risks among younger populations. Raising public awareness and providing targeted training for younger individuals should be prioritized, as their adoption of cleaner energy may also affect older generations to follow suit.

Given the nearly complete electrification in rural China, ensuring households meet their basic needs may no longer be a priority (Jiang *et al* 2020). However, there is still a great proportion of rural households using solid energy. Policymaking should support the shift to advanced forms of energy through mechanisms suited to local contexts. For example, improving cookstove and providing behavioral interventions (e.g. health and education) can reduce respiratory infections, and the latter is expected to be more cost-effective (Yu 2011).

Energy consumption behaviors also play a role in mitigating health impacts. Lack of awareness about the negative health impacts of solid fuel use can reduce the willingness to transition towards advanced energy. For example, innovation of cookstove may produce lower average exposures, consequent influencing childhood pneumonia (Smith *et al* 2011). However, in Bangladesh, women often do not perceive the health risks of indoor air pollution, leading to continued use of traditional, free cookstoves (Mobarak *et al* 2012). Similarly, many Chinese rural households are unaware of the health risks associated with burning biomass fuels (He *et al* 2018, Wang *et al* 2022). Therefore, increasing awareness of these health impacts can be fundamental for inspiring a bottom-up shift towards using advanced forms of energy.

One caveat should be considered when interpreting the results. Our focus on the primary cooking fuel may overlook the health impacts of energy stacking, where households use a combination of fuel types. While our analysis provides valuable insights into primary fuel choice, the complexities of mixed energy use may not be fully captured due to data limitations. Future research should explore the health effects of mixed fuel use compared to single fuel use when data become available.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://cfpsdata.pku.edu.cn/#/home.

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Ethics statement

The CFPS project was approved by Biomedical Ethics Committee of Peking University (IRB00001052-14010).

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