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Does vulnerability to household energy poverty affect rural children's cognition?—Empirical study based on CFPS data

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Energy poverty constrains human development and brings many negative impacts, which makes it one of the urgent global problems at present. Compared to cities, rural areas face a more severe problem of relative energy poverty, where children are the first to suffer from relative energy poverty. Thus, portraying the vulnerability of rural children to energy poverty not only helps to identify the relative state of energy poverty in rural households and provides valuable insights into sustainable rural development policies but also effectively guarantees energy security, enhances children's well-being, and comprehensively protects children's development as proposed by the United Nations goals. Therefore, based on summarizing China's experience, this study innovatively constructs a framework for identifying the vulnerability of Chinese rural households to energy poverty, taking a dynamic perspective on energy poverty. It also explores the impact of vulnerability on children's cognitive ability and the mechanism of influence. The study finds that the vulnerability of rural households to energy poverty has a significant inhibitory effect on children's cognitive ability. Heterogeneity analysis shows that such an effect is particularly prominent among low-income households, especially in rural areas of central and western regions, and that the negative impact is greater among female children. By further exploring how the vulnerability of rural households to energy poverty affects children's cognitive ability, it is found that years of schooling, as a mediating variable, can explain this effect. On this basis, we propose policy recommendations aimed at alleviating relative energy poverty and guaranteeing the developmental rights of rural children through macro-regulatory instruments. Based on the results of the study, appropriate countermeasures are proposed with a view to improving the level of energy use among rural children and increasing their well-being.

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Introduction

The United Nations Sustainable Development Goals (SDGs) prioritize both energy and child development as crucial areas in need of sustained attention. From the perspective of the energy sector, energy poverty remains a key issue constraining the sustainable development of countries worldwide. Due to climate change, attention to green development is increasing. In the context of a community with a shared future for mankind, many countries are committed to promoting energy transformation, transitioning from traditional non-renewable energy to renewable one. Previous studies have found that energy poverty can affect individual development, indicating a strong correlation between energy poverty and child development issues. As the important driving force for the future development of a country and implementing socialist modernization, children are conceived of continuous attention worldwide, especially on how to ensure their development through establishing and improving institutional systems. However, due to the dual urban-rural structure, there are still differences between urban and rural children in terms of resource access, education and medical care, and infrastructure equipment. Rural areas experience 2.5 times more multidimensional energy poverty compared to urban areas (Wan G et al., 2024). The incompleteness of grassroots child protection and service mechanisms brings about prominent challenges for rural children's development. Therefore, addressing the issue of ensuring comprehensive and healthy development for rural children should be a priority.

Promoting the all-round development of rural children is both an important element in the strategy of the workforce development strategy and an important instrument for promoting the equalization of public services. Cognitive ability is recognized as an essential psychological condition to accomplish various activities (Deng, 2015), which refers to the brain's ability to process information. Specifically, it is the process of children's brains receiving a series of external information, forming their own unique mental activities through brain processing, and then further constraining and controlling their own behavior (Shao et al., 2009). The childhood stage is a fundamental stage in the development of cognitive abilities, during which children's perceptions of the world are shaped and develop rapidly, with profound and long-lasting effects on their subsequent social life. Children's cognitive ability affects the accumulation of human capital to a certain extent and contributes to or constrains children's personal development. The issue of cleEnsuring clean energy access for rural children is critical not only for their development but also for advancing the nation's green transition. Children are particularly vulnerable to energy poverty. Research indicates that energy poverty can hinder early childhood development, primarily through its effects on living standards and child health (Karmaker et al., 2022). Evidence from China further underscores a link between energy consumption and children's physical health (Han SR et al., 2023). Research on rural areas reveals a significant correlation between the health status of farming households and clean energy consumption, suggesting that children's health is positively influenced by clean energy adoption (Li FL et al., 2011). If energy poverty affects child development, then it is likely to impair children's cognitive abilities. Children's cognitive ability depends on an interplay of genetic and environmental factors, including parental genetics, personal traits, and both home and broader social environments (Guo G & Stearns E, 2002). However, research on pediatric cognitive ability has focused more on genetic factors and social environment, for example, breastfeeding may affect children's cognitive ability and make them show subtle advantages in early memory. The role of energy access in children's cognitive development remains largely unexplored. To address this, we measure household energy poverty vulnerability from a dynamic perspective to explore how energy poverty impacts children's cognitive development and identify specific pathways through which this impact occurs. Finally, we propose actionable policy strategies to mitigate the impact of energy poverty on rural child development, ultimately supporting the goal of sustainable, green development for future generations.

Based on this, this paper selects the survey data from the CFPS database and takes the vulnerability of rural households to energy poverty as the entry point, with a view to answering the following questions: How does household energy poverty dynamically manifest itself in China's rural areas at present? Does the state of energy poverty in a household affect the cognitive ability of the children? How does the vulnerability to energy poverty of a household affect the cognitive ability of the children? After exploring the above questions, this paper proposes policy recommendations based on the empirical results.

Literature review

Energy poverty vulnerability. Despite improvements in living standards, China, as the world's largest developing country, still faces significant urban-rural disparities that restrict rural households' access to modern, clean energy, thereby intensifying rural energy poverty. Historically, China's energy-poor population who relied on traditional bioenergy were mainly clustered in rural areas in the northeast and west, and the urban-rural differences in clean energy use were obvious, with the income level of rural residents, energy prices, the level of energy infrastructure, and the abundance of bioresources being the main factors affecting the regional differences (Li S & Li L, 2020). Energy poverty in rural Chinese households worsens overall poverty levels. Additionally, unclean cooking energy in rural households significantly reduces individual educational attainment and increases the probability of being unhealthy (Jie E, 2021). Numerous studies on China's energy poverty reveal that while absolute energy poverty has been mitigated through electricity access, rural areas still struggle with access to high-quality, clean energy. More and more scholars are moving beyond a one-dimensional view of China's energy poverty, working toward a multidimensional framework for a more comprehensive assessment of energy poverty (Shi X & Zhou YH, 2023).

In recent years, people have gradually realized that energy poverty is not a simple resource scarcity problem and that it cannot be described from a unidimensional perspective. Plummer, in his research on energy poverty, has developed the most original conception of energy poverty vulnerability and believes that we should look for a wider perspective on energy poverty, that is, to explore the continuing impacts of energy poverty (JL Plummer, 1981). With the introduction of the multidimensional perspective, household income, energy efficiency, and energy prices have been used to depict and measure energy poverty (Ambrose & Aimee R, 2015; Hills J, 2011). Energy poverty vulnerability examines energy poverty from a broader perspective that explores the continuous impacts of energy poverty (Sovacool, Benjamin K, et al., 2021). Energy poverty is a dynamic condition in which households can enter or exit as a result of changing conditions related to housing status and social and economic dynamics. (Bardazzi et al., 2024) Energy poverty vulnerability reflects this changeable state, describing the likelihood of an individual or household falling into energy poverty. Unlike the previous static view of energy poverty, this approach provides an ex-ante prediction, dynamic view of energy poverty, allowing for forward-looking identification of households that are likely to fall into energy poverty in the future, and helps governments to target strategies to prevent these households from falling into poverty in the future. It has been suggested that the configuration of the core elements of energy poverty can determine a country's ability to protect its population from energy poverty, which is known as structural energy poverty vulnerability (Bouzarovski S & Tirado Herrero S, 2017). This definition presents energy poverty as a micro phenomenon resulting from a macro problem, showing the probability of a country's energy poverty breaking out. By the same token, the energy poverty status of children depends on the energy poverty vulnerability of the households in which the member lives. Energy price affordability is not the same across household types, and household size, gender of household members, employment status, labor force status, geographic location, etc., can lead to different energy poverty vulnerabilities, which in turn affects an individual's energy poverty (Meyer et al., 2018). Household energy poverty vulnerability in this study refers to the probability that a household will fall into energy poverty in the future, defined as the likelihood that the quality of clean energy use by an individual or household will fall below the general level of clean energy use in society as a result of exposure to certain risks. This concept assesses a household's resilience to energy poverty during short-term external market shocks, especially when income capacity remains relatively unchanged. A higher vulnerability to energy poverty suggests a greater likelihood of future reliance on non-clean energy sources, which means that the household's energy poverty status is likely to persist for a longer period of time and be more adversely affected.

Scholars generally measure energy poverty vulnerability by developing a comprehensive indicator system to assess regional vulnerability levels. For example, Robinson et al. characterize the socio-spatial variation in regional energy poverty vulnerability through a range of indicators related to energy efficiency, building stock instability, household financial capability, and energy consumption practices and demand (Robinson, Mattioli, 2020). Castaño-Rosa proposes an innovative index for energy poverty vulnerability analysis based on monetary, energy, and thermal comfort factors: the Index of Vulnerable Households (Raúl Castao-Rosa et al., 2020). Other approaches to assessing energy poverty vulnerability include Robinson and Mattioli's study on geographic characteristics of energy vulnerability. They combined household energy poverty with transportation energy poverty to obtain a dual energy vulnerability map (Robinson, Mattioli, 2020). In Poland, Karpinska used multivariate linear regression to identify energy-poor households and then analyzed the region's energy vulnerability using principal component analysis (Karpinska L & Miech S, 2020). There are also a number of indicators and methodologies that have been used to measure energy poverty vulnerability, such as econometric analyses, the level of thermal occupancy of the average home, thermal comfort, and analyses based on the energy efficiency rating of homes (Legendre B & Ricci O, 2015). Due to the complexity of energy poverty, a combination of indicators is needed to capture the various vulnerabilities. Future studies might benefit from using a dashboard of energy poverty indicators rather than a single indicator for a more nuanced understanding (Bortolotti L et al., 2024). Overall, research on energy poverty vulnerability assessment remains largely exploratory.

Theoretical analysis and research hypothesis. From a physiological point of view, the combustion of conventional biomass exposes family members to indoor air pollution, which increases the likelihood of developing asthma, lung cancer, and cardiovascular and respiratory diseases (Adusah-Poku, F & Takeuchi K, 2019). Energy poverty also causes low vision, malnutrition and respiratory diseases. Air pollutants from the burning of traditional fossil fuels may exhibit neurotoxic effects that directly affect the development of the central nervous system in children, resulting in neurological damage to the child's brain according to preliminary biological, epidemiological, and econometric studies (Cooper DH & Farran DC, 1988). Empirical studies have also shown an association between air pollution, and childhood neural development and autism (Lyall et al., 2014). This implies that there may be a high correlation between energy poverty vulnerability and children's cognitive development. Studies have also found that those who receive more health resources in embryo and infancy have better grades. Moreover, children from low-income families benefit more from early health inputs (Wu J et al., 2021). Since energy poverty can compromise children's health, it may, in turn, hinder their cognitive development because of problems with their physical health. From this, we propose the following hypothesis:

H1: Household energy poverty vulnerability has a significant negative impact on rural children's cognitive ability.

H2: Household energy poverty vulnerability affects rural children's cognitive abilities by impairing their physical health.

Piaget's theory of cognitive development posits that cognitive growth is largely driven by a child's interaction with their environment. From the perspective of the family environment, the most obvious consequence of energy poverty is the exacerbation of poverty, often acting both as a cause and as a result of economic poverty (Casillas et al., 2010). Families experiencing energy poverty are often economically disadvantaged as well, limiting their capacity to invest in early childhood development. This lack of resources can result in inadequate nutritional support for mothers during pregnancy and early childhood. Inadequate nutrition during early childhood development is often cited as a source of cognitive deficits in children (Dendir & Seife, 2014). There are also studies that directly show that socioeconomic status directly affects child development (Bradley & Corwyn, 2002). Low socioeconomic status is associated with declining child scores in motor, emotional, cognitive, and language development in the first two decades of life (Sebastián J & Lipina, 2017). Consequently, inadequate financial support in energy-poor families during early childhood can result in inadequate or delayed cognitive development. Based on this, we propose Hypothesis 3:

H3: Household energy poverty vulnerability affects rural children's cognitive abilities by reducing household economic inputs in child development.

Human cognition progresses from perception and thought to the structured representation of the external environment. A key component of cognition is the effective expression of sensory experiences through language, with social education playing a crucial role in shaping this process (Nie, 2020). Inefficient energy use in energy-poor households has forced more members to participate in the collection of daily energy use, this results in the compression or elimination of children's learning time. This leads to decreased learning opportunities and knowledge acquisition, with school-age children, particularly girls, experiencing reduced educational time (Masera et al., 2000). Even the high opportunity cost of learning can make energy-poor families choose to take their children out of school to contribute to family production (Helmers C & Patnam M, 2011). Since learning can broaden one's horizons, increase one's ability to think abstractly, and form new perceptions in an iterative manner as a major process of exercising the thinking ability of the subject, the compression or elimination of children's learning time results in less knowledge acquisition and decline in their ability to learn, potentially impairing their cognitive abilities. Based on this, we propose Hypothesis 4:

H4: Household energy poverty vulnerability affects rural children's cognitive ability by squeezing children's education time.

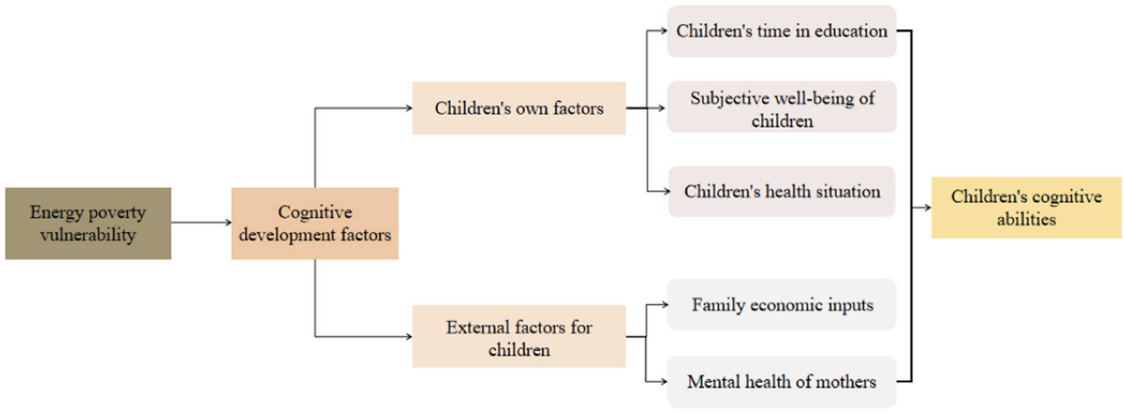

Fig. 1 Analytical framework for the impact of energy poverty vulnerability on rural children's cognitive ability.

Psychologically, an inability to meet basic energy needs can increase levels of depression, stress, and anxiety, leading to lower life satisfaction (Lin B & Okyere MA, 2020). Chronic energy poverty generates emotional stress, which has a subtle impact on children's psychological development as they grow up, and children in energy poverty are more prone to emotional problems such as low self-esteem, increased anxiety and depression, which affects children's sense of well-being (Quanda et al., 2021). Sustained unhappiness can heighten anxiety, depression and other stressful emotions, erode children's sense of self-identity and self-efficacy, and affect their learning effort, thus affecting their cognitive development (Ge CX et al., 2021). Based on this, we propose Hypothesis 5:

H5: Household energy poverty vulnerability affects rural children's cognitive ability by weakening children's sense of well-being.

As children grow, their cognitive processing abilities improve, with parents playing a vital role in the formation of children's cognition (Xi YZ et al., 2017). Early parental influences, particularly maternal physical and mental health, affect children's cognitive expression and understanding. Poor maternal health can reduce children's intake of high-protein foods, which has a significant negative impact on their cognitive abilities with children in low-income families being more affected than those in high-income families (Li JY & Shen Z, 2021). Empirical evidence suggests that maternal mental health significantly influences the emotions, behavior, cognitive abilities, and health of rural children, with impacts greater than those of paternal health (Propper et al., 2007). In energy-deficient households, mothers may need to spend more time collecting traditional fuels or earning money to buy cleaner fuels, thus spending less time caring for their children. Insufficient clean energy use can also lead to increased psychological stress for mothers. As direct caregivers of children, mothers spend more time with their children, and their status may be more likely to influence children's cognition.

H6: Household energy poverty vulnerability affects rural children's cognitive ability by negatively affecting maternal mental health.

To summarize, we construct an analytical framework to examine how energy poverty vulnerability impacts the cognitive abilities of rural children (see Fig. 1).

Methods

Household energy poverty vulnerability calculation model. This study utilizes the ELES model, proposed by Luich in 1973, which builds on the linear expenditure system (LES) model to measure the energy poverty line, in which the variable is exogenized by replacing the total consumption expenditure V with the income I, while the marginal budget share is replaced by the marginal propensity to consume, which makes the estimation of the parameters possible (Zhang WA, 2007). The reasons for choosing the ELES model include: the data required for the estimation coincide with the microdata in the CFPS; exploring the residential energy demand in terms of basic demand and excess demand reduces the arbitrariness of the delineation of the energy poverty line under the traditional single-indicator; and calculating the energy poverty line through the OLS regression, which is in line with the actual situation (Liu et al., 2020). The basic expression of the ELES model is as follows:

$$P_{\mathrm{i}}Q_i = P_i q_i + \beta_{\mathrm{i}}\left(I - \sum_{i=1}^{n} p_i r_i\right)$$

The model assumes that under a given level of income and price, the consumer first satisfies his basic demand for a good or service *Piqi*, and of the remainder, allocates it proportionally between consumption of the ith good and savings. Processing the above equation yields:

$$p_i q_i = \left(p_i r_i - \beta_{\mathrm{i}} \sum_{i=1}^{n} p_i r_i\right) + \beta_{\mathrm{i}} I$$

When the cross-section data is a sample, it is assumed that the prices of goods are the same in the same cross-section relative to different levels of income, and therefore both $p_i r_i$ and $\sum_{i=1}^{n} p_i r_i$ are constant constants, so the above equation is changed to the following econometric model:

$$C_i = \partial_i + \beta_{\mathrm{i}} I + u_i$$

Where ∂_i and β_{i} are the parameters to be estimated and u_i is the random perturbation term, the equation is estimated using least squares estimation to obtain the values of the parameters to be estimated, which in turn yields the residents' basic demand for the ith commodity. In this study, the basic demand for household per capita energy consumption expenditure, i.e., the energy poverty line *X*, is first calculated based on the scalable linear expenditure model, in preparation for the subsequent measurement of energy poverty vulnerability.

In measuring energy poverty vulnerability, this paper refers to the idea of Vulnerability to Expected Poverty measurement (Huang CW et al., 2010), which considers the energy poverty vulnerability of an individual or a household in period t to be the likelihood that their energy expenditure will be below the energy poverty line in period $t+1$, in order to complete the measurement of energy poverty vulnerability.

Basic expression: $VTEPit = P(Ci, t+1 \leq x)$

Where *VTEPit* denotes the energy poverty vulnerability of subject i in period t, *Ci, t + 1* exhibits the energy consumption expenditure of subject i in period t + 1 of the measurement, and *P(Ci, t + 1 ≤ x)* is meant to be the probability that the energy consumption expenditure of subject i is below the energy poverty line of *x*, *i.e.*, the energy poverty vulnerability, in period t + 1.Based on the final calculation, if the probability of subject i falling into energy poverty in the future is more than 50%, then subject i is considered to have a high vulnerability to energy poverty, is likely to fall into energy poverty in the future, and is more affected by energy poverty.

Measurement model. In this paper, we choose a multiple linear regression model to study the effect of household energy poverty vulnerability on children's cognitive ability, and the regression model is as follows:

Model 1:$Y = \beta_0 + \beta_1 EP_{vull} + \varepsilon_i$

Model 2:$Y = \beta_0 + \beta_1 EP_{vull} + \beta_2 X + \varepsilon_i$

Where the main explanatory variable Y is "cognitive ability of rural children"; the core explanatory variable EP_{vull} is "vulnerability to household energy poverty"; X is the control variable, which includes the child's own factors, parental factors, and household economic factors; β_0、β_1 and β_2 are the coefficients to be estimated for the explanatory variables; and ε_i is the randomized disturbing term.

When conducting the mediation test, we refer to the mediation effect model proposed by Wen Zhonglin to analyze the process and mechanism of the impact of energy poverty on rural children's cognition (Wen ZL, 2014). The model is as follows:

$$RZ = cEP_{vull} + \beta X + \varepsilon_1 \quad (1)$$

$$median = aEP_{vull} + \beta X + \varepsilon_2 \quad (2)$$

$$RZ = cEP_{vull} + bmedian + \beta X + \varepsilon_3 \quad (3)$$

median is the mediating variable, EP_{vull} is household energy poverty vulnerability, *RZ* is rural children's comprehensive cognitive ability, and$X$ is the control variable. Model (1) analyzes the impact of household energy poverty vulnerability on rural children's comprehensive cognitive ability. In model (2), a captures the effect of household energy poverty vulnerability on the mediating variable*median*. The $c^{'}$ coefficient is the effect of household energy poverty vulnerability on rural children's general cognitive ability after controlling for mediating variable *median*. The mediating effect is:$c = c^{'} + ab$.

Data description. The China Family Tracking Survey (CFPS) database is a nationally representative large-scale tracking survey program, and the survey data in the database can reflect more comprehensively the changes in China's society, economy, demographics, education and health. In accordance with *The Convention on the Rights of the Child*, introduced by the United Nations in 1989, this paper defines a child as any person under the age of 18 years. This study uses data from the child pool in the CFPS2018 database to match children's parents and then matches the aggregated data of family members in the family pool to finally obtain detailed data on families and family members. The city sample was then culled. After data matching, screening and cleaning, a final sample of 1061 valid rural children was obtained (this sample included all children in each household).

Variable construction. (1) *Core explanatory variables*. When measuring energy poverty vulnerability, the energy poverty line is first measured by drawing on the ELES model proposed by *Luich* in 1973 based on the Linear Expenditure System model (LES) (Zhang WA, 2007). Then we refer to the idea of Vulnerability to Expected Poverty (VEP) estimation for the measurement. The relevant variables selected refer to Mr. Huang's study, including household size, household assets, total government subsidies, household income, household indebtedness, and household consumption expenditures (Huang CW et al., 2010). Meanwhile, considering the substantial difference between energy poverty and poverty, this study added some variables affecting energy consumption, such as home tidiness, commonly used fuels, whether the household is energy-poor, and indoor air purification. In addition, in order to qualify individual characteristics for measuring energy poverty vulnerability, the study selected individual variables: gender, age, age squared, education, health, well-being, and a province dummy. This completes the measurement of energy poverty vulnerability. An individual's or household's vulnerability to energy poverty in period *t* is the likelihood that their energy expenditures will be below the energy poverty line in period $t+1$. The final variable values are expressed as probabilities, and the closer the probability is to 1, the probability is higher that the household will fall into energy poverty in the future.

(2) *Explained variable*s. The CFPS2018 database has nationally standardized test scores for children's phrase test questions and math test questions. Referring to previous studies, we measured the respondents' memory ability by using the scores of the word test and the respondents' ability to reason in number sequences by using the scores of the math test (Huang GY & Xie Y, 2017). In order to reduce errors and the intergroup differences of the variables, the study first calculated the average of the children's word test scores and math test scores, and then standardized the average of the children's word test scores and math test scores to calculate the final children's cognitive ability scores to measure the explanatory variable "children's cognitive ability".

(3) *Control variables*. The control variables are categorized into four main groups, which are the child's personal characteristics, the family's economic conditions, and the parents' circumstances. Child characteristics include age, gender, health status, academic stress, and intelligence level. Household economic conditions include total household income, education and training expenditure, food expenditure, and healthcare expenditure. The situation of both parents of the child consists of the parents' level of intelligence and years of education.

(4) *Mediating variables*. During the testing process, rural children's years of education, subjective well-being, health status, the economic expenditure of the family, and the depression situation of children's mothers were respectively used as the proxy variables for the transmission mechanism for the three-step test. In the evaluation of the depression situation of children's mothers, this paper refers to the CES-D score in the CFPS2018 database and combines the CES-D depression quantitative scale with a score of 16 as a criterion for identifying the depressed population. A score of less than 16 is recognized as the non-existence of depression and is recorded as "0", while the opposite is "1", which determines whether the child's mother is in a state of depression or not. The overall description of the variables is shown in Table 1.

Empirical results and analysis

Descriptive statistics. Through the descriptive statistics of the variables (see Table 2), it can be seen that the mean value of the core explanatory variable, household energy poverty vulnerability, is at 0.62. The average energy poverty vulnerability of the sample rural children's households is high, and they are vulnerable to energy poverty in the future. In terms of the explained variables,

Table 1 Table of research variables and definitions.

	Norm	Variable name	Description of variables
Explanatory variables	Household energy poverty vulnerability	Household energy poverty vulnerability	The likelihood that a household will fall into energy poverty in the future, which examines the household's ability to withstand energy poverty, expressed as a probability
Received variables	Cognition of children in rural areas	Children's cognitive abilities	Mean of memory and arithmetic ability scores from the CFPS2018 database, indicating an individual's ability to process, store, and extract external information
Control variable	Individual children	Age	The actual length of an individual's existence from the time of birth to the time of calculation, expressed in years.
		Sex	Physical differences in biologically anatomical individuals, where male = 1, female = 0
		Health status	A certain condition that an individual achieves physiologically in real life. Very healthy = 5, relatively healthy = 4, generally healthy = 3, relatively unhealthy = 2, very unhealthy = 1
		Academic pressure	Individuals are psychologically overwhelmed by the learning process, very much so = 5, relatively much so = 4, average = 3, relatively little so = 2, very little so = 1
		Intelligence level	Individual's intellectual development, expressed as different scores on a scale of 0 to 10
	Family economic situation	Total household income	Sum of all economic income of the household during the year
		Expenditure on education and training	Sum of household expenditures on education and training for the entire economy in one year
		Food expenditure	Sum of all economic expenditures of the household on food during the year
		Expenditures on healthcare	Sum of all financial expenditures on healthcare by the household in one year
	Father's situation	Intelligence level	Individual's intellectual development, expressed as different scores on a scale of 0 to 10
		Educational attainment	Individual's access to schooling, expressed in years
	Mother's situation	Intelligence level	Individual's intellectual development, expressed as different scores on a scale of 0 to 10
		Educational attainment	Individual's access to schooling, expressed in years
Intermediary variable	Rural children's access to education	Children's years of education	Individual's access to schooling, expressed in years
	Subjective well-being of rural children	Subjective well-being of children	Children's subjective perceptual and cognitive overall assessment of their quality of life
	Mental health of mothers of rural children	Depression in children's mothers	Mother's mood. The presence of depression was recorded as "0"; the opposite was recorded as "1".

Table 2 Descriptive statistics of variables.

	Variable name	Average value	Standard deviation	Minimum value	Maximum value
Explanatory variables	Household energy poverty vulnerability	0.62	0.49	0	1
Received variables	Children's cognitive abilities	0.62	0.19	0.11	1
Individual children	Age	13.48	2.57	10	18
	Sex (Male = 1, Female = 0)	0.49	0.50	0	1
	Health status	2,01	0.90	1	5
	Academic pressure	2.77	1.27	0	5
	Intelligence level	5.51	1.26	1	7
Family economic situation	Total household income(per year per unit)	73,505.73	74,137.07	1000	700,000
	Expenditure on education and training(per year per unit)	10,848.32	13,145.47	0	92,000
	Food expenditure(per year per unit)	21,248.02	22,758.17	1200	240,000
	Expenditures on healthcare(per year per unit)	6652.79	19,228.50	0	320,000
Father's situation	Intelligence level	5.26	1.31	1	7
	Educational attainment(year)	8.07	3.65	0	16
Mother's situation	Intelligence level	4.94	1.36	1	7
	Educational attainment(year)	6.30	3.92	0	15
Intermediary variable	Children's time in education(hour per week)	8.58	2.82	1	17
	Children's subjective well-being	8.43	1.78	0	10
	Depression in children's mothers	13.89	3.67	8	24

the mean value of the children's cognitive ability score is 0.62, with a standard deviation of 0.19, reflecting the fact that the cognitive ability of the sample rural children is at an intermediate level, with a small degree of variability between the samples. The lowest cognitive standardized score of the sample rural children is 0.11 while the highest is 1, which shows that there is a high degree of extreme differences in cognitive ability scores among the sample rural children. The mean value of the gender of the children is 0.49, which proves that the gender of the rural children in the sample is distributed more evenly and the sample selection is reasonable.

Benchmark regression results. The regression results (Table 3) show that the energy poverty vulnerability of rural households has a significant negative effect on the cognitive abilities of children. This implies that the dynamic energy poverty status of rural households may affect children's ability to recognize, retain, recognizance and reproduce objective objects to some degree, to the detriment of children's cognitive development, which proves Hypothesis H1. Higher vulnerability to household energy poverty means that the use of clean energy tends to diminish, and traditional biomass combustion exposes household members to indoor air pollution, which increases the incidence of various diseases, and may also damage children's brain nerves, affecting their cognitive development (Adusah-Poku, F & Takeuchi, K, 2019).

After investigating the potential impact of household energy poverty vulnerability on children's cognitive ability, this study further examined other factors that could influence their cognitive abilities (Table 4).

After the addition of control variables, the regression results still show a significant negative correlation between household energy poverty vulnerability and children's cognitive ability, which confirms the results of the baseline regression and also indicates that reducing household energy poverty vulnerability is conducive to the development of rural children's comprehensive cognitive ability. However, the value of the regression coefficient is relatively small, which may be attributed to the fact that basic electricity access in rural China is currently ensured, meaning absolute energy poverty is not widespread. As a result, the developmental use of energy by children is partially guaranteed. Therefore, while the data shows that energy poverty vulnerability does not significantly impact children's cognitive abilities, this observation highlights another critical issue that requires attention: ensuring rural children's access to high-quality energy.

It is also noteworthy that age has a significant effect on children's cognitive abilities. At the children's level, children's cognitive ability improves from year to year as they grow older during childhood. Gullstr and Julie et al. demonstrate the age dependence of cognition, with adolescence being in the developmental stage, adulthood being optimal, middle age declining, and cognitive impairment appearing in the oldest age group (Gullstrand et al., 2022). An individual's health also affects cognitive abilities, as healthier children have better cognitive abilities. Furthermore, rural children's intelligence level is significantly and positively correlated with their cognitive development.

From the viewpoint of family economic status, the cognitive development of rural children is not significantly correlated with the total economic expenditure and total income of the family, but significantly with the family's education and training expenditure and health security expenditure. An increase in the family's education and training expenditure increases children's cognitive ability, while more health expenditure in the family tends to imply that the health of family members is deteriorating, which can be detrimental to children's cognitive development, given that there is a negative correlation between family health expenditure and children's cognitive ability.

Regarding the parents, the regression results indicate that there is a positive ratio between the level of education of parents and the cognitive ability of the children, especially the father's intelligence level is more influential to the cognitive ability of the children. This could be attributed to that the more educated the parents are, the more commitment and attention they give to their children and the more scientific the parenting style is. The study concluded that positive parenting practices facilitate the cognitive development of rural children (Bai Y et al., 2021).

Table 3 Benchmark regression results.

Variable name	Model 1	Model 2
Household energy poverty vulnerability	−0.12*** (−9.88)	−0.08*** (−5.22)
Control variable		Yes
R-squared	No	0.58
Sample size	1061	1061
Constant term	0.68*** (76.15)	−0.12** (−3.06)

**$P < 0.\ 05$, ***$P < 0.\ 01$; numbers in parentheses are t-values.

Table 4 Factors influencing the cognitive ability of rural children.

Norm	Variable name	Model 2
	Household energy poverty vulnerability	−0.08*** (−5.22)
Individual children	Age	0.04*** (19.52)
	Sex (Male = 1, Female = 0)	0.02* (1.85)
	Health status	0.02** (2.95)
	Academic pressure	0.03*** (8.48)
	Intelligence level	0.04*** (9.66)
Family economic situation	Total household income	3.16e-08 (0.44)
	Expenditure on education and training	4.88e-07** (1.20)
	Food expenditure	−2.31e-07 (−0.99)
	Expenditures on healthcare	−7.35e-07*** (−3.59)
Father's situation	Intelligence level	−0.03*** (−5.36)
	Educational attainment	0.006*** (3.95)
Mother's situation	Intelligence level	−0.002 (−0.49)
	Educational attainment	0.004** (2.85)
Constant term		−012** (−3.06)
Sample size		1061
R-squared		0.57

*, ** and *** have the same meaning as above.

Table 5 Test results of instrumental variables.

Norm	Provincial average energy prices
Sargan test	$P = 0.285$
F test	$F = 68.85$

Endogenous treatment. When exploring whether household energy poverty vulnerability has an impact on rural children's cognitive ability, due to the inevitable heterogeneity among individuals, it is possible that children's cognitive ability will be influenced by other unattended variables or that there is an inverse effect between household energy poverty vulnerability and children's cognitive ability. All these might cause discrepancies in the final estimation results. Thus, endogeneity issues need to be emphasized. By performing the Hausman test on the regression model, the results indicate that there is an endogeneity problem that needs to be addressed by introducing an observable instrumental variable. Referring to Nie et al. (2021), this study adopts the average provincial energy prices as an instrumental variable in combination with two-stage least squares (2SLS) to address the endogeneity of the model (Nie et al., 2021). Of course, this instrumental variable could be challenged, with one hypothesis being that an increase in the price of energy might make rural households use less energy, resulting in children not having access to the appropriate energy support and thus affecting their cognitive development. However, it has been shown that the share of energy support in total expenditures in daily life is very low, and even an increase in energy prices is not enough to affect other expenditures (Churchill SA & Smyth R, 2021). Cheng has estimated that the average share of energy expenditures in household income in China is only 7–8% (Cheng Z et al., 2021). In addition, based on China, energy expenditures in rural households are not sufficiently high to affect the cognitive development of children. Energy prices in China are controlled by the state, with minimal price fluctuations and state subsidies to ensure that residents have access to basic energy, which does not correlate with children's cognitive abilities.

After finding this variable, we first tested instrumental variables (Table 5) and obtained a *P*-value of 0.285 through the Sargan test and constrained *F*-test, which is greater than 0.1, proving that there is no over-identification and the instrumental variables are exogenous. The results are significant, suggesting that the instrumental variables are correlated with the endogenous variables, and the *F*-statistic is 68.85, which is obviously greater than 10, indicating that there is no weak instrumental variable. Consequently, average provincial energy prices can serve as an instrumental variable to resolve the model endogeneity issue before performing the 2SLS regression (Table 6).

By comparing the regression results, the 2SLS regression results continue to show that household energy poverty vulnerability negatively affects rural children's cognitive ability, with a 1-unit increase in household energy poverty vulnerability leading to a 0.15-unit decrease in children's cognitive ability. The negative effect of household energy poverty vulnerability on children's cognitive ability remains significant after using the instrumental variables approach to deal with endogeneity and hypothesis H1 is further tested.

Robustness test. To avoid the biased selection of core explanatory variables, this paper chooses the replacement variable method to test the robustness of the model (Table 7). Firstly, the vulnerability of household energy poverty is replaced by household energy poverty, and a dichotomous variable is used to define the current energy poverty status of the household. If the energy consumption of the current year is lower than the energy poverty line, the household is in energy poverty status in that year, as denoted by "1". On the contrary, if the household's energy consumption is above the energy poverty line, the household is not in energy poverty in that year, which is indicated by "0". At the same time, children's cognitive ability will be affected by children's education level. Education can improve children's cognitive ability, and a longer education means the higher cognitive ability of individuals (Lin B & Okyere MA, 2020). Therefore, by replacing the variable "children's general cognitive ability" with

Table 6 Factors influencing cognitive ability in rural children (OLS vs. 2SLS regression results).

	Variable name	OLS regression results	2SLS regression results
Energy poverty	Household energy poverty vulnerability	−0.08*** (−5.22)	−0.15** (−2.28)
Individual children	Age	0.04*** (19.52)	0.03*** (10.91)
	Sex (Male = 1, Female = 0)	0.02* (1.85)	0.02* (−1.82)
	Health status	0.02** (2.95)	0.02** (3.00)
	Academic pressure	0.03*** (8.48)	0.29*** (6.81)
	Intelligence level	0.04*** (9.66)	0.04*** (7.41)
Family economic situation	Total household income	3.16e-08 (0.44)	4.47e-08 (0.51)
	Expenditure on education and training	4.88e-07** (1.20)	4.48e-07 (1.29)
	Food expenditure	−2.31e-07 (−0.99)	−4.10e-07* (−1.65)
	Expenditures on healthcare	−7.35e-07*** (−3.59)	−8.21e-07*** (−3.51)
Father's situation	Intelligence level	−0.03*** (−5.36)	−0.02*** (−5.47)
	Educational attainment	0.006*** (3.95)	0.005** (2.90)
Mother's situation	Intelligence level	−0.002 (−0.49)	−0.005 (−0.10)
	Educational attainment	0.004** (2.85)	0.003** (1.63)
Constant term		−012** (−3.06)	−0.04 (−0.46)
Sample size		1061	1061
R-squared		0.57	0.52

*, ** and *** have the same meaning as above.

Table 7 Table of robustness test regression results.

Variable name	Replacement of explanatory variables	Replacement of explained variables
Household energy poverty vulnerability	−0.54*** (−4.55)	−0.07*** (−7.98)
Control variable	Controlled	Controlled
R-squared	0.21	0.29
Sample size	1061	1061
Constant term	1.42*** (11.45)	0.61*** (5.67)

*** have the same meaning as above.

Table 8 Heterogeneity analysis table.

Heterogeneous grouping	Variable name	Household energy poverty vulnerability	Control variable	Constant term	Sample size	*R*-squared
Household income level	Low-income households	−0.18** (−2.30)	Yes	−0.86*** (−4.76)	114	0.82
	Middle-income households	−0.09*** (−3.49)	Yes	0.13* (1.68)	476	0.51
	Higher-income households	−0.04* (−2.22)	Yes	−0.16** (−2.51)	398	0.68
	High-income households	−0.10*** (−4.23)	Yes	−0.22*** (−4.13)	173	0.90
Region	Eastern region	0.002 (0.10)	Yes	0.10 (1.43)	238	0.60
	Central region	−0.10*** (−4.43)	Yes	−0.15** (−2.73)	286	0.71
	Western region	−0.08** (−2.53)	Yes	−0.21** (−2.70)	339	0.51
Sex	Male children	−0.04* (−1.99)	Yes	−0.27 (−0.42)	563	0.51
	Female children	−0.11*** (−5.05)	Yes	−0.12** (−2.50)	598	0.58

*, ** and *** have the same meaning as above.

children's years of schooling. After replacing the explanatory and explained variables, respectively, the model regression results remained significant, indicating the robustness of the model.

Heterogeneity test. (1) *There is heterogeneity in household income levels, and this variation directly affects household consumption*. As a result, the vulnerability to energy poverty differs among households with different income levels. Moreover, the cognitive development of children living in various households is influenced differently by their family circumstances, and the extent and nature of this impact may vary. Therefore, the study refers to the statistical approach used in *2018 National Time Use Survey Bulletin* published by the China's National Bureau of Statistics (NBS), and defines low-income households as those with monthly incomes of less than ￥2,000; middle-income households as those with monthly incomes of ￥2,000-￥5,000; higher-income households as those with incomes of ￥5,000-￥10,000; and high-income households as those with monthly incomes households with more than 10,000 yuan. The regression results are shown in Table 8.

First, the regression results show that the income levels of the sample rural households are mostly distributed in the middle-income and higher-income levels, and less in the low-income and high-income households. Second, the coefficients of the impact of energy poverty vulnerability on children's cognitive ability are −0.18 and −0.10 in the low-income and high-income household groups, respectively, which indicates that the negative impact of energy poverty is stronger in these two groups. The living environment of children in low-income rural households still urgent to be improved, as the burning of non-clean energy causes indoor air pollution, the difficulty in using household appliances does not guarantee the comfort of the interior of the house, and the collection of biomass fuels crowds out the children's study time, which all negatively affect the development of children's cognitive abilities. In high-income families, the family has enough money to support the use of clean energy, household appliances and other infrastructure is more complete, and family members who have lived there for a long time already have a high awareness of clean energy consumption. Once a high-income family falls into energy poverty in the future, it will bring a great sense of disparity among the family members. The depressing household atmosphere and poor energy conditions will affect the children living in the household, hindering their cognitive development.

(2) *Regional heterogeneity*. Since energy possession, economic level, and cultural atmosphere are dissimilar, the use of clean energy varies across different regions, so the study explored regional heterogeneity from the three regions of East, Central, and West, and the regression results are shown in Table 8. It is apparent in the regression results that the vulnerability of households to energy poverty may indeed have different impacts on the development of children's cognitive abilities in different regions. Eastern China has better economic development compared to central and western China, and the higher overall economic level also means that farmers in these regions have higher economic incomes and a greater possibility of choosing clean energy. Meanwhile, the eastern regions have a more complete energy-using infrastructure and are more advantageous in terms of access to clean energy there is less energy poverty and low or no vulnerability to household energy poverty, and children's cognitive development in these regions is less likely to be affected by household energy poverty issues, so the regression results are not significant. The economic development of central and western regions is relatively backward and is dominated by hilly, mountainous, and plateau landscapes, with more abundant coal and forest resources, which makes coal and firewood the main energy sources for energy supply. Especially in rural areas, traditional energy is easily the preferred choice for household energy use because of its low price and easy access. Even after clean energy access has been provided and household incomes can largely support clean energy use, farmers persist in choosing to use traditional bioenergy in order to save money, resulting in higher vulnerability to household energy poverty and pollution of the environment in which children grow up.

(3) *Gender heterogeneity among children*. There is gender differentiation in energy poverty, with women and children in rural households being more affected by energy poverty and females facing deeper deprivation in energy poverty (Moniruzzaman M & Day R, 2020). Therefore, it is necessary to explore whether household energy poverty vulnerability affects children differently by gender, starting with male and female children (Table 8).

Table 9 Results of the mediation effect test.

Path	Conduction path a	Ratio	Conduction path b	Ratio	Conduction path c	
1	Household energy poverty vulnerability →	−2.84***	Children's time in education →	10.37***	0.05***	−0.05***
	Children's time in education	(−11.72)	Cognitive abilities of rural children	(34.19)	(3.09)	(−3.46)
2	Household energy poverty vulnerability →	−0.44***	Children's subjective well-being →	−0.11**	−0.19***	−0.003
	Children's subjective well-being	(−2.55)	Cognitive abilities of rural children	(−0.36)	(−10.99)	(−1.23)
3	Household energy poverty vulnerability →	−0.19***	Children's health → Cognitive abilities	0.01**	−0.08***	0.02**
	Children's health	(−11.21)	of rural children	(2.97)	(−5.65)	(3.47)
4	Household energy poverty vulnerability →	−23161.46***	Household economic inputs→	−3271.31	−25,061.78***	−16,764.44
	Household economic inputs	(−5.07)	Cognitive abilities of rural children	(−0.42)	(−5.20)	(−2.04)
5	Household Energy Poverty Vulnerability →	0.38	Mental health of children's mothers →	−0.98	−0.19***	−0.002
	Mental health of children's mothers	(1.03)	Cognitive abilities of rural children	(−1.54)	(−10.56)	(−1.31)

** and *** have the same meaning as above.

Table 10 Sobel test results.

Path	Path 1	Path 2	Path 3	Path 4	Path 5
Z	10.49	1.21	0.71	0.42	0.40
P	0.00	0.27	0.49	0.69	0.82

In the Sobel test results, a mediating effect is considered to be present if $Z > 1.96$ and $P < 0.1$.

Table 11 bootstrap test results (path 3).

Path	effect	95% Conf. interval		P
bs1	Ind-eff	−0.007	0.012	0.47
bs2	Dir-eff	−0.242	−0.151	0.00

Bs1 represents the indirect effect outcome, and bs2 represents the direct effect outcome.

The regression results show that the impact of rural households' energy poverty vulnerability on children's cognitive ability has a clear gender difference, with male children experiencing a smaller and less significantly negative impact and female children experiencing a larger and more significantly negative impact. This suggests that there are differences in the impact of clean energy use in rural areas, particularly in terms of the cognitive development of female children. In other words, female children have less access to clean energy when their families are in energy poverty.

Analysis of impact mechanisms

Test results. From the results of the test of mediating effects (Table 9), it can be seen that all coefficients of path 1 and path 3 are significant after the test of the three-step method, which supports that path 1 and path 3 are valid. Path 2 fails as there is a non-significant coefficient in conduction path c, this may be due to the fact that subjective well-being does not affect children's cognitive development to too great an extent. Further, since the coefficients in conduction path b and conduction path c for path 4 and path 5 are not significant, and path 4 and path 5 are not established. While some studies suggest that economic status is related to children's cognitive ability, our study found that economic status did not act as a mediating variable between energy poverty and children's cognitive ability, probably because the covariance between economic inputs and energy consumption is so strong that they are not sufficient to mediate the relationship. Similarly, mothers' mental health was not found to be a mediator, which may be due to the strong subjective influence of the depression self-assessment scale scores in the data, making the results only indicative.

The three-step method gives a basic indication of the mediating effect. but to better test the reliability of the results of the three-step method, it is necessary to utilize the Sobel test to estimate the mediating variable's share of the total effect by constructing a statistic for the product of the coefficients (Table 10).

According to the results of Sobel test, path 1 passes the Sobel test, which illustrates that the mediating effect in path 1 exists, while path 3 does not pass the Sobel test, so we need to further confirm the validity of path 3. For reconfirming the existence and validity of the transmission mechanism of path 3, we introduced the bootstrap test to reconfirm path 3. In the results of the bootstrap test, the mediating effect is not significant if the interval estimation contains "0" and significant if the interval estimate does not contain "0". The results of the bootstrap test for path 3 are shown in Table 11.

The bootstrap test results show that both bs1 and bs2 exhibit direct effects, but no indirect effects. Meanwhile, the P-value represents the significance and from the significance, only bs2 is significant. The mediating effect is considered to exist only if the indirect effect is significant, so there is no mediating effect for path 3. This demonstrates how children's health cannot be fully utilized to explain why household vulnerability to energy poverty can affect the cognitive abilities of rural children. In summary, the reduction of children's learning time appears to be the most compelling explanation for the cognitive deficits observed in children from households with high energy poverty vulnerability.

Analysis of intermediary mechanisms. Combined with the analysis of the above tests, only the mediating effect of path 1 "Household energy poverty vulnerability → Children's time in education → Cognitive abilities of rural children", is significant and can be used to explain the mechanism of household energy poverty vulnerability's influence on rural children's cognitive ability, which will be briefly analyzed below.

The high vulnerability of households to energy poverty implies the likelihood of the persistence of household energy poverty. In households with limited access to energy resources, where traditional biomass represents the primary source of fuel, family members are compelled to dedicate a significant portion of their time to fuel collection. This inevitably results in a reduction in the time available for family members to spend together or for children to attend school, as much of their time is consumed by fuel collection. The compression or elimination of children's learning time can lead to a decline in their knowledge acquisition and learning capacity, which can directly impact their cognitive abilities. At the same time, rural households with high energy poverty vulnerability have relatively low economic incomes, and most of the children in these households start school late and miss out on early childhood experiences. As a consequence, households with high energy poverty vulnerability tend to have shorter durations of schooling compared to those with low vulnerability. This undoubtedly diminishes the opportunities for rural children to achieve better cognitive development and has a negative impact on their overall cognitive abilities.

In addition, energy poverty vulnerability reveals the poverty status of the household, which in most cases is linked to the economic situation of the household. Cognitive development requires optimal brain development and enhanced socialization skills, and systematic schooling is an important factor influencing children's psychological development. Empirical studies have shown that access to pre-school education has a large positive effect on improving children's cognitive abilities (Yuan YZ & Zhao Y, 2019). From the available data, households with high vulnerability to energy poverty have lower investments in education, which means that households with limited economic conditions and limited total funds will be inclined to invest more in spending to ensure basic living conditions and less in children's education to maintain a basic life. In addition, in families with high vulnerability to energy poverty, parents tend to have a lower awareness of education investment, which also means that they do not have high expectations of their children's education. To balance the family's income and expenditures and alleviate financial pressure, their investment in their children's education may be lower compared to other rural families. All these make children experience more physical labor and less time for education in their early growth process, with deficiencies in knowledge acquisition and skill development, which affects the development of their early intelligence and, thus, their cognitive development.

Conclusion and policy implications

Conclusion. By measuring the energy poverty vulnerability of Chinese rural households and analyzing its impact on children's cognitive ability, we draw the following conclusions:

(1) In the relative energy poverty stage, energy poverty is manifested by the relative lack of individual energy-using capacity, and rural households may still present energy poverty in the future after clean energy access. This dynamic relative energy poverty phenomenon is demonstrated through energy poverty vulnerability. From the measurement results, among the 1061 samples, there are 684 households with high energy poverty vulnerability, roughly accounting for 64.4% of the total sample size, which reveals that the problem of relative energy poverty is more prominent in rural China and that the problem of non-clean energy uses in rural areas in the future needs to be urgently solved. Across rural areas, the mean value of energy poverty vulnerability is 0.62, which means that more than half of the people in rural areas are at risk of returning to energy poverty. The study reveals that energy poverty vulnerability in China is generally higher in the western regions than in the eastern regions, and greater in coastal areas compared to inland areas, which to a certain extent demonstrates that the level of economic development and the improvement of the energy infrastructure can help to reduce the vulnerability of residents to energy poverty. Furthermore, the study indicates a gender disparity in energy poverty, with women more susceptible to energy poverty than men.

(2) The results of the baseline regression indicate a significant negative effect of household energy poverty vulnerability on children's cognitive ability. The higher the household energy poverty vulnerability is, the lower the cognitive ability of rural children is.

(3) The results of the heterogeneity test show that there is heterogeneity in the impact of household energy poverty vulnerability on children's cognitive ability. In detail: first, families of different income levels are affected differently, and low-income and high-income families' energy poverty vulnerability on children's cognitive ability is greater. The reason for this is that low-income families who have limited economic capacity are more prone to failing to pay for energy in the face of a possible increase in energy consumption, plunging them into a state of energy poverty. While high-income families have better energy equipment and need more clean energy, a decrease in clean energy consumption will increase the sense of disparity in the lives of family members, affecting their psychological state and, thus, the cognitive ability of children. Second, there is regional heterogeneity in the impact. The impact of household energy poverty vulnerability on rural children's cognitive ability is smaller in the eastern region, which benefits from a more developed economy and better energy infrastructure. Third, there are gender differences in impacts, with female children's cognitive abilities being more affected by household energy poverty vulnerability. Under the influence of traditional thinking in some rural areas, development resources are usually skewed in favor of male children, and female children face greater pressure and exploitation in accessing resources.

(4) The results of the mechanism analysis test show that household energy poverty vulnerability can affect the cognitive development of rural children by influencing the number of years of schooling. Households with high vulnerability to energy poverty require large amounts of fuel to meet their daily needs, and children are forced to join in the collection of energy for daily needs, which takes time away from their schooling. Rural households with high vulnerability to energy poverty are often economically disadvantaged, with parents having to balance the allocation of household funds to maximize the family's profitability, and children's educational inputs are reduced when subsistence spending accounts for the majority of household expenditures. Moreover, parents usually lack awareness of early education in households with a high vulnerability to energy poverty, making children generally older at school, less educated and cognitively impaired in the early stages of development. Therefore, reducing energy poverty in rural households can help improve the cognitive ability of rural children and contribute to the accumulation of rural human capital.

Policy implications. The evidence from China has the following policy implications for countries around the world to alleviate energy poverty and contribute to the development goals of the United Nations:

First, countries should accurately grasp the stage of energy poverty development and realize dynamic energy poverty alleviation. For instance, the relativization of energy poverty is quite obvious in China's new phase. The government should establish a mechanism to identify energy poverty vulnerability in rural areas and categorize households experiencing relative energy poverty. By monitoring their energy poverty status, accurate energy subsidies can be provided to those with high vulnerability, ensuring their access to clean energy for fulfilling children's daily needs.

Second, governments should strive to improve modern energy information flow channels in villages, improve energy transportation channels, and enhance the stability of rural energy supply. Through strengthening the information technology empowerment of the rural energy industry, the rural energy industry should be promoted to complete the low-carbon transition. In addition, governments need to encourage the intelligent development of the rural energy industry, empower the rural energy industry through information technology, realize the transparency of energy demand information, accelerate the research and promotion of energy storage technology, increase the proportion of rural energy storage industry, and establish promote efficient clean energy "production, supply, storage and marketing" system.

Thirdly, increase investment in rural energy infrastructure construction, overhaul and improve rural energy transportation pipelines, continue to implement the subsidy policy for rural residents to buy household appliances, and encourage rural households to equip themselves with solar energy facilities. The energy equipment in some public areas should be overhauled and updated in due course, to establish a network of energy-using facilities in public areas.

Fourthly, raising residents' awareness of energy use. Energy poverty is related to personal energy awareness and energy habits. In some rural areas, the traditional concept of conservation, coupled with the long-term use of traditional biomass fuels for energy dependence, has led some rural households to choose to use non-clean energy sources, even when clean energy facilities are available and clean energy prices are acceptable. For this reason, governments should actively disseminate the benefits of clean energy use in rural areas, emphasize the negative impacts of non-clean energy combustion, and emphasize clean energy use in a variety of ways, including seminars, videos, radio broadcasts and slogans, to enable rural children to develop an awareness of clean energy use and green energy habits from an early age.

Fifthly, governments must increase support for rural female children to access and utilize clean energy while prioritizing their rights and interests in energy use. Furthermore, promoting the concept of equality is crucial to ensure equitable opportunities for both sexes in accessing clean energy.

This paper also has certain limitations. On the one hand, in terms of data collection, this paper heavily relies on cross-sectional data from the CFPS, which may have limitations in accurately reflecting the energy usage patterns of rural households. On the other hand, while exploring the pathway through which household energy poverty vulnerability affects the cognitive abilities of rural children, this paper only identified children's years of education as a mediating variable. Future studies could delve deeper into other potential factors and aspects related to this relationship.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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LY: conceptualization, methodology, writing—original draft. ZT: supervision, modeling, and writing—review. LZ: programming, and editing. SM: conceptualization, data resources. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

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Additional information

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