

Health Benefits of the Green and Low-Carbon Transition of Rural Household Energy Use: Research Progress and Prospects

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Abstract

The green and low-carbon transition of rural household energy use sits at the intersection of China's "dual carbon" goals and the Healthy China strategy. Following the evidence chain of "energy transition—household air pollution—population health", this paper systematically reviews research published in leading Chinese and international journals. The energy ladder hypothesis and the fuel stacking perspective constitute the theoretical foundation of household energy transition. Household air pollution (HAP) from solid fuel use substantially harms respiratory, cardiovascular and overall health, as documented by global burden-of-disease studies and Chinese cohort evidence. Randomized controlled trials and quasi-natural experiments confirm the causal health benefits of clean energy transition. Micro panel evidence based on CHARLS and related data has grown rapidly, yet gaps remain in causal identification, regional representativeness, mechanism testing and heterogeneity analysis, especially for southwestern provinces such as Sichuan. Future research should strengthen causal identification with multi-wave panel data, conduct locally grounded assessments, and advance the monetization of health benefits and policy scenario simulation.

Keywords

Rural Residential Energy; Clean Energy Transition; Household Air Pollution; Health Benefits; Energy Poverty; Sichuan Province

1. Introduction

At present, about 2.1 billion people—roughly a quarter of the world's population—still cook over open fires or inefficient stoves fueled by kerosene, biomass (wood, animal dung and crop residues) and coal, and the resulting household air pollution (HAP) is among the most important environmental health risks in low- and middle-income countries 1). The Global Burden of Disease (GBD) study estimated that HAP from solid fuels caused approximately 2.31 million

premature deaths and 91.5 million disability-adjusted life years (DALYs) in 2019, ranking ninth among attributable risk factors for global deaths 2); although the exposed share of the population continues to decline, the burden remains concentrated in rural areas of sub-Saharan Africa, South Asia and East Asia 3). China is rewriting this picture through one of the world's fastest residential energy transitions: over the past three decades, income growth, energy infrastructure development and policies such as biogas construction, the “coal-to-gas” and “coal-to-electricity” programs and clean heating in northern China have shifted rural cooking and heating away from solid fuels toward electricity, natural gas and liquefied petroleum gas 4). Yet the transition is regionally uneven: constrained by resource endowments, incomes, habits and geography, firewood, straw and coal still account for a considerable share in less-developed rural areas such as the southwestern mountains, and “fuel stacking”—the concurrent use of multiple fuels—is widespread 5), Sichuan, a major western province in terms of population and agriculture, combines a long biogas tradition in the basin plains with persistent solid-fuel dependence in mountain and ethnic-minority areas, offering a typical setting for evaluating the health benefits of the green and low-carbon transition of rural household energy use.

Against the backdrop of the “dual carbon” goals and the Healthy China strategy, the Implementation Plan for Green and Low-Carbon Energy Transition of Sichuan Province and the Carbon Peaking Implementation Plan for the Energy Sector of Sichuan Province explicitly call for increasing the supply and consumption of clean energy in rural areas and promoting the electrification and decarbonization of cooking and heating. Scientifically evaluating the health benefits of this transition can provide health-dimension justification for energy policy and identify environmental entry points for health policy, thereby achieving policy synergy across energy, environment and health. Following the logic of “theoretical foundations—evidence of harm—evidence of benefits—mechanisms and heterogeneity”, this review first surveys the literature thematically and then offers a critical appraisal and outlook, so as to provide a literature base and an analytical framework for empirical research on the health benefits of the green and low-carbon transition of rural household energy use in Sichuan Province.

2. Theoretical Foundations: Energy Ladder, Fuel Stacking and Rural Household Energy Transition

2.1. The Energy Ladder Hypothesis and Its Revisions

The classic account of household energy transition is the “energy ladder” hypothesis. Based on evidence from Zimbabwe, Hosier and Dowd proposed that as household income rises, cooking fuels climb a ladder from biomass to coal or kerosene and then to liquefied petroleum gas (LPG) and electricity, with income regarded as the core driver of fuel upgrading 6). Leach linked this framework to household energy

transition in developing countries, noting that climbing the ladder entails both efficiency gains and declining pollution exposure 7). Subsequent research has systematically revised this linear presumption. Using micro data from Mexico, Masera et al. found that rural households rarely abandon traditional fuels completely; instead, they hold portfolios of multiple fuels, so that transition should be understood as a gradual change in fuel-mix structure—“fuel stacking” rather than one-for-one substitution 8). A meta-analysis of the energy ladder literature by van der Kroon et al. shows that the direction and magnitude of the effects of income, fuel prices, energy availability and household characteristics vary across contexts, so that the ladder holds in some settings and fails in others 9). This theoretical thread implies that evaluating the health benefits of energy transition must go beyond a binary “clean versus solid” classification and attend to continuous changes in fuel portfolios and use intensity.

Beyond income, the determinants literature has identified fuel relative prices, energy availability and infrastructure, household demographics, education, housing characteristics and social norms 9). Prices and subsidies reshape fuel portfolios through relative costs; availability constraints explain why some high-income households remain locked into traditional fuels; and education and information promote clean-fuel adoption through health-awareness channels. These findings extend the energy ladder from a single-income logic to a household production decision under multiple constraints, and they provide the theoretical basis for controlling confounders in health-benefit evaluation.

2.2. Facts and Drivers of China’s Rural Residential Energy Transition

Domestic research in China began in the late 1990s. Based on field surveys of 2,253 rural households in Shanxi, Guizhou and Zhejiang Provinces, Shi et al. systematically documented the reality of “multi-energy complementarity”, in which commercial energy coexists with firewood in rural China 5). Using data from the Chinese Residential Energy Consumption Survey (CRECS), Wu and Zheng re-examined the energy ladder hypothesis and found that the number of fuel types used by households follows an inverted-U path with income: cooking energy can upgrade spontaneously as income grows, whereas administratively driven policies such as “coal-to-electricity” have, to some extent, suppressed the income effect 10). At the macro level, Tao et al. quantified the evolution of China’s rural cooking and heating energy structure from 1992 to 2012 through a representative national survey, confirming the continuous decline of coal and firewood shares and the rapid rise of electricity and LPG 4).

2.3. Regional Practice of Energy Transition in Sichuan

Rural energy research on Sichuan has distinctive regional features. Taking biogas construction in Sichuan as an example, Fang et al. analyzed the pathways and

performance of rural energy development under the new countryside construction program 11). Based on a household survey in Sichuan, Chen et al. examined the choice mechanisms of household biomass energy use and their policy implications for improving rural livelihoods 12). Using household survey data from Liangshan Prefecture, Zhai and Fu found that household size, education, income and ethnic customs significantly affect residential energy consumption: higher-income households are more inclined to use commercial energy, and better-educated households are more receptive to clean energy 13). Overall, Sichuan's rural energy transition enjoys a first-mover advantage in biogas utilization but faces practical constraints on phasing out solid fuels in mountain and ethnic-minority areas; the pronounced intra-provincial gradient implies that health-benefit evaluation must rest on local evidence.

3. Solid Fuels, Household Air Pollution and Health Hazards: The Evidence Map

3.1. Global Disease Burden and Epidemiological Evidence

Incomplete combustion of solid fuels releases large quantities of fine particulate matter (PM_{2.5}), carbon monoxide and polycyclic aromatic hydrocarbons; in poorly ventilated dwellings, indoor smoke can contain fine particles at levels up to 100 times the acceptable level, and women and children, who spend the most time near the hearth, are the most exposed 1). Zhang and Smith provided a foundational review of measurements, health impacts and interventions for HAP from coal and biomass fuels in China 14). Using the Prospective Urban and Rural Epidemiology (PURE) cohort covering 11 low- and middle-income countries, Hystad et al. found solid fuel use to be significantly associated with cardiovascular events and all-cause mortality 15). For China, estimates by Yun et al. based on emission inventories and exposure-response relationships show that residential solid fuel combustion contributes significantly to ambient PM_{2.5} pollution and its health impacts, so that cleaning up the rural cooking and heating sector yields prominent health co-benefits 16). In terms of disease spectrum, the health hazards of HAP cover lower respiratory infections, chronic obstructive pulmonary disease (COPD), ischemic heart disease, stroke, lung cancer, type 2 diabetes, adverse birth outcomes and cataracts 2). GBD research further shows that although the age-standardized burden rate of HAP has fallen sharply since 1990, the absolute burden has declined slowly because of population growth and aging, and the improvement of clean cooking access is too slow to meet the Sustainable Development Goals on schedule 3), suggesting that the phase-out of solid fuels is not an automatic outcome of development but requires sustained policy intervention.

3.2. Cohort Evidence from China: From Xuanwei to CKB and the Rural Sichuan Cohort

China's local evidence has evolved from endemic-disease investigations to large-scale cohorts. The high lung-cancer incidence associated with smoky coal burning in Xuanwei, Yunnan Province, has become a classic case in environmental epidemiology: the prospective cohort of Lan et al. confirmed that household stove improvement significantly reduces lung cancer risk 17); based on more than three decades of follow-up, Barone-Adesi et al. further confirmed the persistence of coal-related lung cancer risk and the durability of intervention benefits 18). In recent years, the China Kadoorie Biobank (CKB) has taken the evidence to a new level: Yu et al. found that long-term solid-fuel cooking in rural areas is significantly associated with elevated risks of cardiovascular and all-cause mortality 19); in the urban sample, persistent solid-fuel users had a 19% higher risk of all-cause mortality and 24% and 43% higher risks of cardiovascular and respiratory mortality, respectively 20). Particularly important for this review, based on a prospective cohort in a rural area of Sichuan, Qiu et al. found solid fuel use to be significantly associated with cardiovascular diseases and all-cause mortality 21), providing direct local cohort evidence for southwestern China.

4. Health Benefits of Clean Energy Transition: Experimental and Quasi-Experimental Evidence

4.1. International Randomized Controlled Trials

The gold standard of causal evidence comes from randomized controlled trials (RCTs). The RESPIRE trial in Guatemala randomly assigned households to chimney stoves, and the intervention reduced children's carbon monoxide exposure by about 50% on average. Although the intention-to-treat reduction in physician-diagnosed pneumonia was not statistically significant (RR = 0.84, 95% CI: 0.63–1.13), severe pneumonia fell significantly by about 30%, and exposure–response analysis showed that every 50% reduction in exposure significantly lowered the risk of physician-diagnosed pneumonia by about 18% 22). This indicates that the magnitude of exposure reduction and intervention adherence are decisive for health gains. Thereafter, the multicountry Household Air Pollution Intervention Network (HAPIN) trial using LPG established a more rigorous testing framework, moving the field from “stove improvement” toward the evaluation paradigm of “clean fuel substitution” 23).

4.2. Quasi-Natural Experiments from China's Heating and Energy Policies

China's rich policy practice provides fertile ground for quasi-experimental research. Exploiting the Huai River heating boundary as a discontinuity, Almond et al. found that coal-based winter heating in northern China significantly raised total suspended particulate (TSP) concentrations and shortened life expectancy 24); Chen et al. estimated that sustained exposure to high TSP concentrations reduced

the life expectancy of northern residents by about three years 25); using more refined data, Ebenstein et al. estimated that every 10 $\mu\text{g}/\text{m}^3$ increase in PM10 shortens life expectancy by about 0.6 years 26). Fan et al. exploited winter temperature shocks to identify the seasonal increase in mortality caused by coal-fired heating—the “winter choke” effect 27). Regarding clean heating policies, the cost–benefit assessment of Zhou et al. shows that the environmental and health benefits of clean heating retrofits in northern China far exceed household costs 28); based on Beijing data, a difference-in-differences analysis by Lee et al. shows that the coal-to-clean-heating policy significantly reduced the risk of acute myocardial infarction 29). Chinese scholars have reached consistent conclusions: using China Health and Nutrition Survey (CHNS) data and a Logit-DID model, Fan et al. found that the Air Pollution Prevention and Control Action Plan (the “Air Ten Measures”) significantly reduced the incidence of diseases highly related to air pollution, with more pronounced health effects among women, urban residents and the younger and older age groups 30).

4.3. Micro Panel Data Evidence on the Transition–Health Nexus

With the opening of large micro databases such as the China Health and Retirement Longitudinal Study (CHARLS) and the China Family Panel Studies (CFPS), transition–health research has entered the stage of micro causal identification. Liu et al. examined the health impacts of cooking fuel choice in rural China 31). Using China Labor-force Dynamics Survey data with instrumental variables, Fang and Liu found that the residential energy structure significantly affects rural residents’ health risks, with low-income groups facing higher risks, thereby highlighting the health implications of “energy poverty alleviation” 32). Based on multi-wave CHARLS panels, Yu et al. confirmed that HAP from solid cooking fuels significantly increases the risk of chronic respiratory diseases, whereas switching to clean energy reduces that risk 33).

Regarding identification strategies, micro research has evolved from ordinary least squares to instrumental variables, fixed effects and difference-in-differences. Early studies compared health differences between solid-fuel and clean-fuel users after controlling for observable characteristics 31); subsequent work introduced instrumental variables such as village energy supply, terrain and historical energy endowments to mitigate self-selection bias 32); and fixed-effects models based on multi-wave panels further removed time-invariant individual heterogeneity. Nevertheless, reverse causality—households experiencing health shocks may change their fuel choices—and time-varying confounders cannot be fully ruled out, which is precisely why quasi-experimental and micro panel evidence need to corroborate each other.

5. Mechanisms and Heterogeneity: Gender, Income and Age

The core mechanism through which solid fuels harm health is HAP exposure: PM2.5 from incomplete combustion penetrates deep into the alveoli and enters the bloodstream, inducing oxidative stress and systemic inflammation and thereby causing respiratory and cardiovascular diseases 14). Behavior and time constitute a second pathway: cooking is mainly undertaken by women, so women and children bear the highest exposure 1); firewood collection also consumes substantial labor time, forming a transmission chain of “energy poverty—time poverty—health impairment”. Housing conditions and ventilation facilities further moderate exposure intensity 32).

The energy poverty literature provides a framework for understanding the distributional effects of transition health benefits. Liddell and Morris reviewed the health costs of fuel poverty. At the micro-behavioral level, the health gains of energy transition are realized through at least three channels: the concentration channel, whereby clean fuels directly reduce kitchen and indoor PM2.5 and CO concentrations 14); the time channel, whereby eliminating firewood collection and inefficient cooking reallocates labor time toward employment, care and rest; and the household resource channel, whereby the budget released by changes in energy expenditure can be spent on medical care and food. Notably, fuel stacking implies that adopting a single clean fuel does not necessarily reduce exposure proportionally; only a deep phase-out of solid fuels delivers the expected health gains 8-9). In terms of heterogeneity, Ding et al. found that rural women’s off-farm employment alleviates household energy poverty by raising household income, reducing women’s housework time and enhancing their decision-making power; women and low-income groups benefit more from the health effects of clean energy 30-32); and older adults are the most sensitive group because of physiological frailty and longer indoor stays.

6. Critical Review and Future Directions

6.1. Major Contributions of the Existing Literature

Taken together, the literature has formed a relatively complete evidence chain. First, the energy ladder and fuel stacking theories provide a mature framework for understanding rural household energy transition 6-9). Second, from global burden-of-disease estimates 2-3) to classic cohorts such as Xuanwei and CKB 17-20), epidemiological evidence on the health hazards of solid fuels is substantial. Third, RCTs represented by RESPIRE and HAPIN 22-23) and quasi-experimental studies represented by the Huai River policy and clean heating programs 24-29) provide high-quality evidence for causal inference on the transition–health nexus. Fourth, empirical research based on micro databases such as CHARLS and CFPS has grown rapidly in recent years 31-32), and energy poverty and health inequality are receiving increasing attention.

6.2. Limitations of the Existing Literature

First, causal identification remains insufficient. Most micro studies rely on cross-sectional or short-panel correlational analysis; reverse causality and omitted-variable bias (income, housing and hygiene behavior) are rarely addressed, and instrumental-variable and quasi-experimental designs remain limited in rural cooking settings. Second, regional evidence is unbalanced. Quasi-experimental evidence is concentrated in northern heating areas, whereas southwestern China features cooking-dominated exposure, a mixed biogas–firewood energy structure and mountain terrain that hampers pollutant diffusion, making northern evidence hard to extrapolate; existing Sichuan studies are either single-county cohorts (21) or descriptive analyses (12, 13), lacking causal evidence from province-representative micro panels. Third, the mechanism “black box” remains unopened: most studies use fuel type as an exposure proxy without indoor PM_{2.5} measurements or individual exposure assessment, and fuel stacking makes the binary “clean versus solid” classification mismeasure true exposure (8). Fourth, heterogeneity and dynamic effects are understudied: conclusions on gender, income and age heterogeneity are scattered, and because transition is gradual and reversible, single-period comparisons cannot capture its dynamic health returns. Fifth, the monetization of health benefits and policy cost–benefit evaluation have just begun (28), providing little marginal guidance for policy optimization.

6.3. Future Directions

Future research can be deepened in the following directions. First, multi-wave micro panel data combined with two-way fixed-effects and dynamic panel models can be used to identify the causal health effects of household energy structure transition, mitigating reverse causality and omitted-variable bias. Second, research should be grounded in regional contexts; for western provinces such as Sichuan that combine a biogas tradition with solid-fuel dependence, locally representative panel evidence is urgently needed. Third, the mechanism black box should be opened by combining indoor air pollution monitoring, time-use and cooking-behavior data. Fourth, heterogeneity along gender, income and age dimensions should be systematically examined to identify vulnerable groups. Fifth, the monetization of health benefits and policy scenario simulation should be advanced to quantify the health gains of higher clean-energy penetration. These directions are precisely the entry point of the project “Research on the Health Benefits of the Green and Low-Carbon Transition of Rural Household Energy Use in Sichuan Province”: relying on CHARLS multi-wave panel data covering about 30,000 rural households in 12 prefectures of Sichuan and a two-way fixed-effects model, the project evaluates the health benefits of energy transition and their group heterogeneity, and quantifies the health gains of clean energy promotion through policy scenario simulation, thereby directly responding to the gaps in the existing literature.

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