Household energy consumption in Henan province: Current status, challenges, and optimized development pathways

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Abstract: Energy consumption serves as a critical link between economic development and ecological protection, and it is one of the key pathways to achieving the "dual carbon" goals. As the most populous province in China, Henan's household energy consumption holds a significant position in the country's overall energy usage, making it a region of notable representativeness and research value. This paper examines the temporal evolution and spatial distribution characteristics of household energy consumption in Henan Province, systematically analyzing the major challenges encountered in its transition toward clean energy, and proposes optimized development pathways. The study finds that while the total household energy consumption in Henan Province has continued to grow in recent years, its growth rate has gradually slowed. The energy structure has shown a trend toward cleaner energy, with the proportion of electricity and natural gas usage increasing significantly. However, challenges such as uneven development of regional energy infrastructure, insufficient adoption of clean energy, low energy efficiency, and weak public awareness of green consumption remain prominent, hindering the modernization and clean energy transition of household energy consumption. To address these challenges, this paper recommends optimizing regional energy infrastructure, strengthening policy support for clean energy, promoting efficient and energy-saving equipment, improving household energy efficiency, and popularizing green energy consumption concepts. These measures aim to accelerate the transition of household energy consumption in Henan Province toward modernization and cleaner energy. The findings not only provide a scientific basis for optimizing Henan's household energy structure but also offer valuable insights for energy transitions in other regions across China.

Keywords: Clean energy, Energy efficiency, Energy structure optimization, Henan Province, Household energy consumption.

1. Introduction

Energy is a crucial pillar of economic development and a key area for achieving green development and the "dual carbon" goals. As a major global energy consumer, China has seen its total energy consumption continuously increase in recent years. Within this context, household energy consumption, as a significant component of terminal energy demand, occupies a central role in the nation's energy transition efforts toward cleaner and more efficient use.

Henan Province, as China's most populous region, has a representative and research-worthy scale and structure of household energy consumption. The province exhibits distinct regional characteristics in its household energy consumption patterns. According to the latest statistics, household energy consumption accounted for approximately 18% of Henan's total energy consumption in 2022 [1]. The growth in household energy consumption is closely linked to the province's socioeconomic development. In 2022, the per capita disposable income of urban and rural households in Henan reached 38,500 RMB and 18,700 RMB, respectively—approximately twice the figures from a decade ago [2]. Economic growth has driven the rapid adoption of clean energy in urban households, with natural gas network coverage exceeding 90%. However, rural households, constrained by limited economic capacity, insufficient clean energy infrastructure, and the price advantage of traditional fuels, continue to rely

heavily on firewood and coal. This reliance significantly limits the province's progress in achieving cleaner household energy consumption.

The expansion of energy consumption has also brought environmental and social challenges. In particular, the incomplete combustion of traditional fuels in rural households is a major source of air pollution and carbon emissions. Data show that household energy consumption accounted for about 18% of Henan's energy-related carbon emissions in 2020, with over 80% originating from rural households [3]. Additionally, the inefficient use of fuels such as firewood and biomass not only leads to energy waste but also exacerbates smog and fine particulate matter pollution, posing health risks to residents [4].

To address the dual challenges of growing household energy consumption and environmental pressures, Henan Province has actively promoted the transition to clean energy in households. Various measures have been implemented to optimize urban and rural energy consumption structures. For example, the "coal-to-electricity" and "coal-to-gas" policies have yielded initial results in some rural areas, raising the clean heating coverage rate in rural households to 43% by 2022. Moreover, photovoltaic projects have been installed in over 30,000 rural households. Urban households have also made progress in adopting energy-saving technologies, such as the increased use of smart home devices and high-efficiency heat pumps. Nevertheless, challenges persist due to disparities in income levels and regional infrastructure, hindering the clean energy transition in household consumption.

Given these issues, an in-depth study of the current status, characteristics, and major challenges of household energy consumption in Henan Province has significant theoretical and practical implications. On the one hand, it can provide scientific support for Henan's efforts to achieve its "dual carbon" goals and clean energy transition. On the other hand, the findings can serve as a reference for optimizing energy structures in similar regions across central China. Based on this, this paper systematically analyzes the spatial and temporal characteristics of household energy consumption in Henan Province, identifies the challenges faced, and proposes optimized development pathways and policy recommendations, aiming to contribute to regional energy transitions and low-carbon development.

2. Temporal and Spatial Characteristics of Household Energy Consumption in Henan Province

The temporal and spatial characteristics of household energy consumption in Henan Province are shaped by a combination of economic development, regional resource endowments, policy orientation, and household consumption behavior. Analyzing the temporal trends and spatial distribution patterns of energy consumption helps to comprehensively understand the dynamic features of Henan's energy use and provides a scientific basis for policymaking.

2.1. Temporal Evolution Characteristics

In recent years, the total volume and structure of household energy consumption in Henan Province have undergone significant changes driven by socioeconomic development, technological progress, and policy initiatives.

2.2.1. Growth in Total Household Energy Consumption

Between 2010 and 2022, the total household energy consumption in Henan Province increased steadily, albeit with a noticeably slowing growth rate. Data indicate that total household energy consumption rose from 20.44 million tons of standard coal in 2010 to 43.55 million tons in 2022, more than doubling over the period. However, the annual growth rate declined from over 5% before 2010 to approximately 1.8% after 2020.

This trend reflects the stabilization of household energy consumption growth, influenced by factors such as slowing population growth and the adoption of energy-saving technologies.

From 2010 to 2015, household energy consumption in the province grew rapidly, increasing from 20.44 million tons to 26.73 million tons of standard coal, with an average annual growth rate of approximately 5.5%. In contrast, between 2015 and 2022, growth rates slowed significantly, with the 2022 growth rate dropping to 1.6%.

The deceleration in total energy consumption growth is primarily attributable to the following factors.

Changes in Urban and Rural Population Structure: A decrease in population in some rural areas and a reduction in household size have led to weaker growth in household energy consumption.

Wider Adoption of Clean Energy Equipment: The increasing use of energy-efficient devices, such as energy-saving stoves and smart meters, has enhanced energy utilization efficiency and slowed overall consumption growth.

Figure 1.
Total household energy consumption in Henan province (2010–2022).
Source: Henan Statistical Yearbook

Figure 1 illustrates the continuous growth in total household energy consumption in Henan Province, with a noticeable decline in growth rates after 2015. Since 2020, the growth rate has remained below 2%, indicating that improvements in energy consumption structure and efficiency are having a positive impact.

2.1.2. The Trend Toward Cleaner Energy Structure

In recent years, the structure of household energy consumption in Henan Province has progressively shifted toward cleaner energy sources. The proportion of traditional fuel usage has declined significantly, while the share of clean energy—including electricity, natural gas, and liquefied petroleum gas (LPG)—has steadily increased. By 2022, the level of clean energy consumption in Henan households had improved considerably compared to 2010, reflecting the positive impact of policy guidance and rising living standards.

The use of traditional fuels has dropped sharply. Data show that per capita coal consumption decreased from 53.89 kg in 2010 to 28.19 kg in 2022, a decline of 47.7%. The reduction in coal use as a primary household energy source is primarily attributed to the implementation of "coal-to-electricity" and "coal-to-gas" policies, as well as the promotion of clean heating equipment in rural areas.

The share of clean energy consumption has increased dramatically, particularly for electricity and natural gas:

- **Electricity**: Electricity has become a vital household energy source, with per capita consumption rising from 288.2 kWh in 2010 to 880.79 kWh in 2022, a growth rate of 205.5%. This growth is driven by the widespread adoption of household appliances and improvements in residents' living standards.
- **Natural Gas**: Per capita natural gas consumption surged from 3.4 cubic meters in 2010 to 40.35

cubic meters in 2022, an almost 12-fold increase. The expansion of natural gas pipelines and the widespread adoption of gas infrastructure were the primary driving forces behind this growth.

- **Liquefied Petroleum Gas (LPG)**: Although the growth of LPG usage is less pronounced than that of natural gas, its consumption has stabilized at around 13–14 kg per person per year since 2020, primarily in areas not covered by natural gas infrastructure.
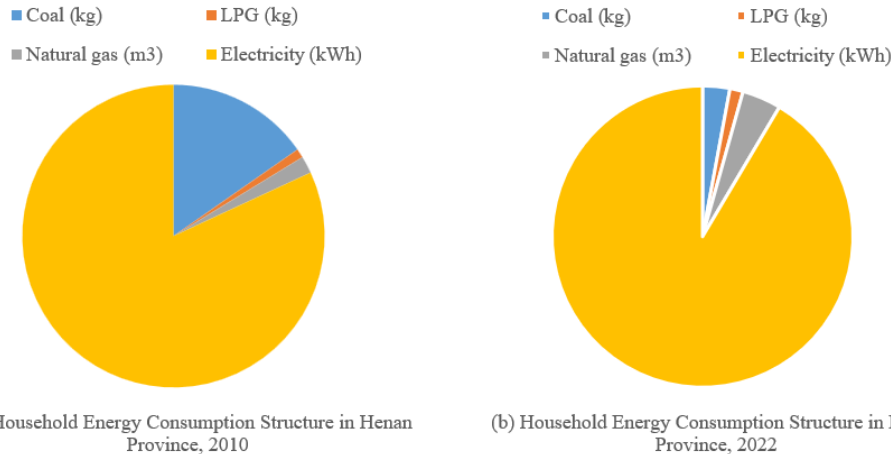

(a) Household Energy Consumption Structure in Henan Province, 2010

(b) Household Energy Consumption Structure in Henan Province, 2022

Figure 2.
Changes in household energy consumption structure in Henan province (2010 and 2022).
Source: Henan Statistical Yearbook

Figure 2 illustrates a steady decline in coal usage, which decreased from 53.89 kg in 2010 to 28.19 kg in 2022. In contrast, the use of natural gas and electricity has increased significantly, with electricity consumption growing by more than 200%, making it the dominant energy source in household energy consumption.

2.1.3. Increase in Energy Consumption Intensity

The overall intensity of household energy consumption has continuously increased. In 2022, per capita household energy consumption reached 441.10 kilograms of standard coal, which is 2.45 times higher than the 179.79 kilograms recorded in 2010. Despite the significant growth in total consumption, the trend toward a cleaner energy structure is highly evident. The proportion of traditional coal in total consumption has decreased sharply, while the share of clean energy sources, such as electricity and natural gas, has risen rapidly.

2.2. Spatial Distribution Characteristics

The spatial distribution of household energy consumption in Henan Province is influenced by the combined effects of urban-rural economic development levels, natural conditions, and energy supply infrastructure, exhibiting significant regional disparities.

2.2.1. Differences in Regional Economic Levels

The regional distribution of household energy consumption in Henan Province is closely linked to economic development levels. Economically developed areas, particularly urban hubs such as Zhengzhou and Luoyang, have a higher degree of clean energy adoption, with a significant increase in the use of modern energy sources such as electricity and natural gas. In contrast, in economically underdeveloped regions, such as Nanyang and Xinyang, traditional fuels like coal and biomass continue to play a dominant role.

Economically Developed Areas: Represented by the Zhengzhou metropolitan area, these regions boast high clean energy adoption rates. Household coverage of electricity and natural gas leads the

province, and new energy technologies such as photovoltaic power generation have also been widely implemented.

Economically Underdeveloped Areas: In regions such as southwest and southeast Henan, lower household incomes and insufficient infrastructure result in a higher reliance on traditional fuels like coal and firewood in household energy consumption.

2.2.2. Influence of Topography and Resource Endowments

The regional distribution of household energy consumption in Henan Province is significantly influenced by topography and natural resource endowments, leading to notable differences in energy consumption patterns across various geographical areas.

Plain Areas: In regions such as the eastern Henan plain and northern Henan, convenient transportation and well-developed infrastructure contribute to higher clean energy coverage rates. The widespread adoption of natural gas networks and distributed photovoltaic projects has significantly improved the energy structure. Data indicate that clean energy accounts for over 70% of total household energy consumption in these areas.

Mountainous and Hilly Areas: In regions such as the southwestern Henan mountains and the Taihang Mountains, geographical constraints have delayed the development of clean energy infrastructure. Traditional energy sources, such as firewood and biomass, continue to dominate household energy consumption, while the adoption of clean energy remains at a relatively low level, leaving room for improvement.

2.2.3. Differences in Infrastructure Development Levels

The level of energy infrastructure coverage is a critical factor influencing household energy consumption. The uneven development of infrastructure across regions in Henan Province directly affects the proportion of clean energy usage in households.

Natural Gas Coverage: Although the overall natural gas coverage rate in the province has reached 68%, significant regional disparities persist. In metropolitan areas such as Zhengzhou, natural gas adoption exceeds 90%, while in remote mountainous regions and some economically underdeveloped areas, the coverage rate is only around 30%.

Photovoltaic Power Projects: In recent years, Henan Province has made significant efforts to promote distributed photovoltaic power generation. For instance, in Xixia County, Nanyang, more than 1,200 households have installed photovoltaic power stations, greatly improving their energy consumption structure. However, the adoption of this new energy technology remains uneven across the province.

2.3. Summary

The temporal and spatial characteristics of household energy consumption in Henan Province exhibit significant dynamic changes and regional disparities.

From a temporal perspective, total household energy consumption has continued to grow in recent years, though the growth rate has gradually slowed, indicating that household energy consumption is entering a stabilization phase. Meanwhile, the energy structure has improved notably, with a sustained increase in the use of clean energy sources such as electricity and natural gas, alongside a sharp decline in the use of traditional fuels like coal and firewood. This trend toward cleaner energy is attributed to policy guidance, technological advancements, and rising living standards.

From a spatial perspective, the distribution of household energy consumption structures is significantly influenced by regional economic levels, topographical conditions, and infrastructure coverage. Economically developed areas, such as the Zhengzhou metropolitan region, predominantly rely on electricity and natural gas, achieving higher rates of clean energy adoption. In contrast, remote mountainous areas and economically underdeveloped regions still depend heavily on traditional fuels like firewood and coal, with relatively low levels of clean energy usage.

Overall, while household energy consumption in Henan Province is steadily improving, challenges remain. The uneven levels of clean energy adoption across regions and insufficient clean energy

infrastructure in certain areas highlight the need for targeted efforts. Moving forward, it is crucial to tailor strategies to regional characteristics, combining technology promotion with policy guidance to further enhance energy efficiency and advance the comprehensive modernization and clean energy transition of household energy consumption.

3. Challenges in Household Energy Consumption in Henan Province

Although Henan Province has made progress in optimizing its energy consumption structure and improving energy efficiency, its transition toward cleaner and more modern household energy consumption still faces multiple challenges. These challenges include significant regional disparities in energy consumption structures, insufficient infrastructure development, limited adoption of clean energy, low energy consumption efficiency, and inadequate public awareness of green consumption. Together, these issues pose serious constraints on Henan's progress toward achieving its "dual carbon" goals.

3.1. Significant Regional Disparities in Energy Consumption

Household energy consumption structures and patterns vary significantly across different regions in Henan Province. These disparities are shaped by factors such as economic development levels, natural resource endowments, and infrastructure coverage rates.

Uneven Clean Energy Adoption Rates: Economically developed regions, such as the Zhengzhou metropolitan area, have high rates of clean energy adoption, with electricity and natural gas serving as the primary sources of household energy consumption. In contrast, in economically underdeveloped areas such as the southwestern mountainous regions and northern Henan, low infrastructure coverage results in the continued dominance of traditional fuels like firewood and biomass in household energy consumption.

Lagging Infrastructure Development: Clean energy infrastructure in remote mountainous and hilly areas lags behind, with significantly lower coverage rates for natural gas pipelines and distributed photovoltaic power facilities compared to plain regions. Inadequate energy supply networks have become a major bottleneck in achieving cleaner household energy consumption.

Economic Constraints: Household economic capacity directly affects the adoption of clean energy. Low-income households are more likely to rely on traditional fuels such as firewood and coal, which are cheaper, and are less able to afford clean energy equipment like natural gas stoves or heat pump heating systems [5].

3.2. The Need to Further Enhance Clean Energy Adoption

Although policies such as "coal-to-electricity" and "coal-to-gas" have significantly increased the adoption of clean energy in Henan Province, its use still faces several constraints:

Insufficient Policy Support: Clean energy promotion policies are primarily focused on economically developed regions, while underdeveloped and remote areas are less covered. Many households, particularly low-income rural families, are unable to benefit from subsidies or related policies.

Heavy Economic Burden: The high initial costs of adopting clean energy, such as installation fees for gas equipment and the purchase of energy-efficient appliances, pose economic challenges for households. Additionally, in some regions with underdeveloped energy markets, the relatively high cost of clean energy discourages residents from using it.

Lack of Awareness and Education: Many residents, especially in rural areas, lack an understanding of the advantages of clean energy. Limited promotion and education regarding its economic and environmental benefits hinder broader adoption.

3.3. Energy Consumption Efficiency Needs Improvement

The overall efficiency of household energy use in Henan Province still has significant room for improvement, particularly in rural areas where the widespread use of inefficient energy equipment results in substantial energy waste [6].

Outdated Equipment: Many households continue to use traditional coal stoves and firewood burners, which are not only energy-inefficient but also cause severe environmental pollution, posing a major challenge to energy-saving efforts [7].

Uneven Technology Adoption: The promotion of high-efficiency energy-saving equipment, such as energy-efficient stoves and smart water heaters, is concentrated mainly in urban areas, while rural areas receive inadequate attention. Additionally, the high costs of energy-saving equipment make it unaffordable for some low-income families.

Lagging Awareness and Behavior: A lack of awareness about energy conservation and limited knowledge of efficient energy utilization methods persist among some households, leading to widespread energy waste.

3.4. Insufficient Public Awareness of Green Consumption

The promotion of green consumption concepts is critical for advancing clean energy adoption. However, residents in Henan Province still have limited awareness of clean energy and energy-saving practices [8].

Lack of Knowledge About Clean Energy: Many residents are unaware of the economic and environmental benefits of clean energy sources such as electricity and natural gas. This issue is particularly pronounced in rural areas, where households continue to rely heavily on traditional fuels like coal and firewood.

Path Dependence on Energy Consumption Habits: Long-standing reliance on traditional energy usage has reinforced behavioral inertia. For example, coal and firewood remain widely used due to their low cost, and residents have shown limited short-term acceptance of new energy sources.

Inadequate Promotion and Education: Awareness campaigns about energy conservation, emission reduction, and clean energy usage are largely concentrated in urban areas. In contrast, rural areas receive significantly less attention, hindering the dissemination of green consumption concepts.

4. Optimized Development Pathways for Household Energy Consumption in Henan Province

In light of the specific challenges faced by household energy consumption in Henan Province—such as regional disparities in energy consumption, insufficient clean energy adoption, low energy efficiency, and weak public awareness of green consumption—this section proposes the following targeted development pathways to comprehensively enhance the cleanliness, modernization, and efficiency of household energy consumption.

4.1. Optimize Regional Energy Infrastructure

Balance Infrastructure Development: Prioritize the development of natural gas pipelines, distributed photovoltaic power systems, and microgrids in underdeveloped areas such as the southwestern mountainous regions and northern Henan. Establish regional small-scale energy stations to ensure reliable and clean energy access for households in remote areas, thereby reducing regional disparities in energy consumption.

Increase Financial Support: The government should allocate additional funds specifically for energy infrastructure development in remote areas to improve the accessibility of clean energy in rural regions. For example, provide targeted subsidies for installing photovoltaic equipment in low-income households to reduce dependence on traditional fuels.

Strengthen Urban-Rural Energy Integration: Promote the interconnection of urban and rural energy infrastructure to enable efficient dispatch of clean energy sources, such as natural gas and electricity, across urban and rural areas. This approach can alleviate energy supply instability in remote regions.

4.2. Strengthen Clean Energy Adoption

Expand Policy Coverage: Enhance the implementation of "coal-to-electricity" and "coal-to-gas" policies in regions with weaker clean energy adoption, such as western and southern Henan. Explore

incorporating biomass energy conversion into clean energy promotion efforts to meet diverse regional energy demands.

Reduce Clean Energy Costs: Strengthen economic incentives for clean energy equipment. For instance, increase subsidy amounts for equipment purchases, and provide zero-interest or low-interest loans for low-income rural households to reduce the cost of acquiring equipment such as gas stoves and heat pumps, thereby facilitating the transition of household energy consumption.

Diversify Promotion Methods: In economically disadvantaged areas and regions where natural gas pipelines are difficult to establish, promote cost-effective technologies such as energy-saving stoves and high-efficiency biomass stoves. Simultaneously, scale up the development of distributed photovoltaic systems and small-scale biogas projects in these areas.

4.3. Improve Household Energy Efficiency

Promote the Adoption of Energy-Efficient Equipment: Accelerate the widespread application of high-efficiency energy-saving devices across the province. Phase out inefficient coal stoves and firewood burners commonly used in rural areas. Provide policy subsidies and technical training to promote modern energy-efficient equipment, such as smart water heaters and energy-saving air conditioners, to significantly enhance household energy efficiency.

Strengthen R&D and Application of Energy-Saving Technologies: Focus on developing low-cost, high-efficiency energy-saving devices tailored to the characteristics of Henan Province. Examples include smart energy-saving stoves or low-power electric heating devices suitable for rural areas. Facilitate large-scale production and market adoption of these devices to reduce their cost.

Optimize Energy Use Behavior: Conduct energy-saving behavior guidance and education to encourage residents to optimize their energy consumption patterns. For instance, implement time-of-use electricity pricing policies to guide residents to use electricity during off-peak hours, enabling more efficient energy use and reducing waste.

4.4. Promote Green Energy Consumption Concepts

Enhance Awareness and Education: Launch province-wide clean energy awareness campaigns using television, radio, social media, and other platforms to highlight the economic and environmental benefits of clean energy. Focus on rural areas by disseminating energy-saving knowledge and information about subsidy policies.

Encourage Green Consumption Habits: Introduce incentive mechanisms to encourage residents to adopt green consumption habits. For instance, implement a green energy points reward program, where residents can earn points for reducing the use of traditional fuels like coal and firewood and increasing their clean energy consumption.

Promote Community Pilot Demonstrations: Establish pilot programs in selected communities to showcase green energy consumption models. Examples include creating zero-carbon demonstration communities and popularizing smart energy management systems, such as home energy monitoring systems. Use visualized results to demonstrate energy-saving achievements and encourage broader participation in green energy use.

5. Conclusion

This study examines household energy consumption in Henan Province, analyzing its temporal and spatial characteristics, major challenges, and optimization pathways. It provides policy recommendations to promote the transition of household energy consumption toward modernization and clean energy adoption. The findings are as follows:

Household energy consumption in Henan Province demonstrates clear temporal evolution trends and regional distribution characteristics. Over time, total household energy consumption has grown, albeit at a slower pace. The adoption of clean energy has steadily increased, while the use of traditional fuels has declined significantly, indicating structural optimization in household energy consumption. Spatially, energy consumption patterns are heavily influenced by economic development levels, natural

resource endowments, and infrastructure availability. Economically developed regions have embraced clean energy at higher rates, whereas underdeveloped areas remain reliant on traditional fuels.

Despite progress, significant challenges remain. The transition toward cleaner and more modern energy consumption is constrained by pronounced regional disparities, insufficient clean energy adoption, low energy efficiency, and limited public awareness of green consumption. These obstacles hinder the expansion of clean energy usage and impose additional pressure on achieving Henan Province's "dual carbon" goals.

To address these issues, this study proposes several optimization pathways. Regional infrastructure development must be balanced by accelerating the deployment of clean energy facilities in underserved areas, such as natural gas pipelines and distributed photovoltaic systems, to reduce energy disparities. Expanding clean energy coverage through supportive policies and financial incentives is essential to make these options more accessible to households. Promoting high-efficiency energy-saving devices, such as smart appliances, can significantly improve energy efficiency, particularly when combined with efforts to optimize household energy usage behavior. Furthermore, public education on energy conservation and environmental protection should be strengthened to encourage green consumption habits, supported by community-level demonstrations of sustainable energy practices.

This study identifies critical issues and bottlenecks in Henan Province's household energy consumption, offering insights for advancing clean energy transitions at both provincial and national levels. In the future, achieving the "dual carbon" goals will require more precise policies and regional adaptations. Enhanced technological innovation, refined policy design, and increased public participation are necessary to guide Henan Province toward a cleaner, more efficient, and sustainable energy future.

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