Theoretical Economics Letters, 2026, 16(1), 269-298
https://www.scirp.org/journal/tel
ISSN Online: 2162-2086
ISSN Print: 2162-2078

Exploring the Relationship between China's Digital Village Development and Green Energy Consumption among Farmhouseholds: Mechanisms, Evidence, and Policy

Longlong Duan, Yijiayi Li*, Haochen Wang

School of Economics, Sichuan University, Chengdu, China
Email: *31323539@qq.com

How to cite this paper: Duan, L. L., Li, Y. J. Y., & Wang, H. C. (2026). Exploring the Relationship between China's Digital Village Development and Green Energy Consumption among Farmhouseholds: Mechanisms, Evidence, and Policy. *Theoretical Economics Letters, 16,* 269-298.
https://doi.org/10.4236/tel.2026.161018

Received: October 29, 2025
Accepted: February 22, 2026
Published: February 25, 2026

Abstract

Against the backdrop of the "dual carbon" strategy, promoting the green transformation of rural energy consumption structures is a critical issue for achieving sustainable rural development. This paper systematically reviews the literature on the relationship between digital village development and farmers' green energy consumption from three dimensions: theoretical mechanisms, empirical evidence, and policy interventions. Information empowerment holds a fundamental position in driving the green energy consumption transformation among farmers. By resolving information asymmetry and reshaping cognitive frameworks to activate endogenous demand. Findings reveal: First, digital village development drives the transition toward cleaner and more efficient energy consumption among farmers through multiple pathways. These include boosting income and alleviating mobility constraints, reducing search costs and information asymmetry, improving energy accessibility, leveraging peer effects and demonstration effects, and enhancing digital literacy. Second, household energy choice behavior exhibits complex decision-making characteristics, jointly constrained by economic factors such as income constraints, price effects, and resource endowments, as well as non-economic factors including transaction costs, cognitive biases, and behavioral inertia. Third, digital technology adoption significantly promotes clean energy uptake among households, though its effects exhibit heterogeneity across regions, income levels, and education levels. Fourth, policy interventions play a crucial role in driving energy transition. The existing policy framework suffers from a core theoretical flaw, overemphasizing an "economic incentives-driven" logic that mistakenly treats farmers as perfectly rational economic agents, resulting in policy effectiveness falling short of expectations. Economic incentives, information disclosure, infrastructure development, and behavioral nudges each have distinct advantages and limitations, necessitating tailored combinations based on local conditions. This paper identifies gaps in existing research—including insufficient exploration of micro-level mechanisms, lack of long-term impact assessments, and weak studies on policy coordination—and proposes future research directions. It provides theoretical insights and policy implications for advancing the organic integration of digital rural development and green energy transition.

Keywords

Digital Rural Development, Household Energy Consumption, Digital Empowerment, Dual Carbon Goals, Rural Revitalization

1. Introduction

Digital rural development propels China's agricultural and rural modernization while supporting rural revitalization and integrated urban-rural development. It constitutes a core organic component of the "Digital China" initiative in rural areas. Since the 2018 Central Document No. 1 first proposed "implementing the digital village strategy", the state has successively issued a series of top-level design documents, such as the "Digital Village Development Strategy Outline" and the "Digital Agriculture and Rural Development Plan". Digital village construction has now entered a phase of systematic and institutionalized advancement. In this process, the green transformation of rural energy structures also faces the urgent demands of the national "carbon peak and carbon neutrality" strategic goals. However, rural household energy consumption in China still relies predominantly on traditional solid fuels like coal and firewood, resulting in high carbon emissions and environmental pollution that severely threaten residents' health and the achievement of national carbon goals. Against this backdrop, coordinating digital village development with clean energy transition—and exploring the intrinsic mechanisms and feasible pathways for digital empowerment to optimize rural energy consumption structures—has become a critical issue of both theoretical value and practical urgency. Existing research exhibits a prioritization bias in understanding digital empowerment pathways, with information empowerment—rather than economic empowerment—emerging as the core lever for overcoming bottlenecks in rural energy transition. Concurrently, the current policy framework fails to adequately address the "bounded rationality" characteristic in household decision-making. The limitations of its theoretical premises hinder the sustained deepening of policy effectiveness. This paper systematically reviews relevant literature, focusing on the core question of "how digital rural development drives green energy consumption among farmers". It examines theoretical mechanisms, empirical evidence, and policy interventions to provide academic insights for promoting sustainable rural development and achieving the "dual carbon" goals.

2. The Development Process and Logic of Digital Village Construction

Digital village construction holds a pivotal position within China's rural revitalization strategy, serving as a key focal point for advancing rural development while also constituting an indispensable component of the Digital China initiative. Since the 2018 Central Document No. 1 first proposed implementing the digital village strategy, China has established a multi-tiered policy support system for this endeavor. The state has successively issued documents such as the "Outline of the Digital Village Development Strategy" and launched multiple batches of national-level digital village pilot projects. Currently, a working framework characterized by "coordinated planning and holistic advancement" has taken shape, establishing digital village construction as a key pathway to modernize agriculture and rural areas and support rural revitalization.

The scope of digital village development spans multiple dimensions. Scholars have summarized its core elements into five key areas: first, rural digital infrastructure construction; second, rural data resource development and management; third, rural digital industrialization; fourth, rural industrial digitalization; and fifth, rural governance digitalization (Zeng et al., 2021). Existing research has identified multiple mechanisms through which the digital economy supports rural revitalization. Empirical studies by He et al. (2022a) demonstrate that the digital economy drives rural revitalization primarily through two intermediary mechanisms: "technological innovation" and "human capital". Building upon this, Zhang and Luan (2022) further propose three pathways through which the digital economy propels development. First, integrating data elements into agricultural production; second, embedding digital products and services into farmers' daily lives; and third, incorporating digital thinking into rural government services. These pathways can drive agricultural industrial upgrading, enhance farmers' skills, and advance intelligent rural governance. Wang et al. (2021) analyzed the "virtual space" effect, arguing that digital villages empower multiple scenarios—including agricultural production, circulation, and governance—through matching, coordination, and multiplier effects.

Practically, digital village initiatives have yielded outcomes across multiple domains, primarily manifesting in five key scenarios: 1) Smart agricultural production, 2) Efficient rural distribution, 3) Precision-oriented social governance, 4) Intelligent lifestyle transformation, 5) Modernization of cultural perspectivesFor instance, technologies like the Internet of Things and remote sensing monitoring have been deployed. These innovations boost production efficiency and resource utilization, while new business models such as rural e-commerce and live-streaming sales expand distribution channels, helping increase farmers' incomes. Research indicates that the digital economy positively impacts multiple dimensions of rural revitalization, including "prosperous livelihoods", "ecologically livable environments", "civilized rural customs", and "effective governance". While its influence on "thriving industries" has yet to fully manifest overall, its promotional effect is particularly pronounced in western regions. This provides a basis for implementing differentiated regional development strategies (He et al., 2022b).

Overall, despite persistent challenges in digital village development—including inadequate digital infrastructure, shortages of digital talent, and inefficient data-sharing mechanisms (Zhang & Luan, 2022)—China has achieved significant progress in policy guidance, theoretical exploration, and practical application. The integration of the digital economy with agricultural and rural development continues to deepen, injecting new digital momentum into rural revitalization. However, the rapid development of China's rural digital economy contrasts sharply with the persistent and severe energy challenges in rural areas. Currently, traditional solid fuels remain the primary source of energy consumption in rural areas, not only hindering the achievement of the "dual carbon" goals but also posing serious threats to residents' health and the ecological environment. Therefore, in advancing digital rural development, how to coordinate energy transition with digital progress and pursue digital empowerment for energy optimization has become a critical issue for achieving sustainable rural development.

3. Prominent Issues in China's Rural Energy Sector

Against the backdrop of the "dual carbon" goals, energy transition has become a core strategic task underpinning the nation's green and low-carbon development while safeguarding ecological security. As a significant component of China's energy consumption, rural household energy use has grown rapidly—from 96.47 million tons of standard coal equivalent in 2010 to 169.33 million tons in 2022. However, China's rural energy mix has long been dominated by solid fuels such as coal, firewood, and straw. This structure not only results in elevated carbon and pollutant emissions but also poses serious threats to residents' health and well-being. Research indicates that traditional biomass energy still holds a significant position in rural household energy consumption in China (Han et al., 2023). The Third National Agricultural Census Main Data Bulletin (No. 4) reveals that in 2017, 101.77 million rural households (44.2%) used firewood for cooking and heating, while 55.06 million households (23.9%) relied on coal. The widespread use of solid fuels has worsened rural air quality, increasing health risks (Fang & Liu, 2019). Global data indicate that approximately 3.2 million people die prematurely each year due to household air pollution (World Health Organization, 2024), primarily stemming from the incomplete combustion of solid fuels and kerosene during cooking.

Thus, promoting the transition of rural energy consumption toward cleaner, low-carbon sources holds immense practical significance for achieving China's ambitious goals of "reaching peak carbon emissions before 2030 and carbon neutrality before 2060", as well as for building a Healthy China and beautiful rural communities. Consequently, studying the evolution of rural energy consumption patterns is not only an environmental economics issue but also a crucial component of development economics.

It is worth noting that clean energy utilization is a vital component of achieving the dual carbon goals. As a key area for traditional energy consumption, the optimization of the energy structure in rural regions plays a pivotal role in the national carbon reduction process. The "energy ladder" theory posits that as income levels rise, rural households gradually shift away from traditional biomass energy toward cleaner, more efficient modern energy sources (Zhang et al., 2017). Traditional energy sources like coal and firewood, classified as "non-Giffen inferior goods", experience declining demand as income increases (Liao, 2019). Currently, China's rural energy consumption remains in a transitional phase from biomass to commercial energy sources, with structural imbalances and challenges in clean energy adoption still prominent (Liu, 2014; Zhang et al., 2023a). The "Energy Ladder" theory from development economics provides a foundational framework for understanding this phenomenon. Empirical studies consistently demonstrate that households' ascent up this ladder is far from smooth. A substantial number of families remain trapped in the quagmire of "energy poverty" for extended periods, grappling with multiple constraints of energy "availability", "affordability", and "reliability" (Kaygusuz, 2011). This indicates that attributing farmers' energy choices solely to linear income growth severely underestimates the more complex institutional environments, market failures, and behavioral biases influencing their decisions. Thus, a core economic puzzle emerges: Why does the diffusion of green energy technologies and energy-saving behaviors remain so slow in rural areas despite potential economic returns? The answer to this question will determine whether we can unlock the immense potential of digital rural development in addressing China's rural energy challenges. Farmers' energy consumption behaviors are constrained by multiple economic and non-economic factors. Understanding the mechanisms underlying these factors is both a prerequisite for solving this problem and the key to whether digital rural development can genuinely drive a green energy transition.

4. Influencing Factors of Farm Household Energy Consumption Behavior

1) Economic Factors: Beyond Traditional Income and Price

First, income effects and liquidity constraints. Traditional economic analysis focuses intensely on income and price as core variables. Economic factors directly determine rural residents' energy choices through budget constraints, serving as the primary driver for transforming energy consumption structures. From the perspective of income effects, rising income levels enable households to gradually reduce dependence on traditional energy sources and shift toward clean energy consumption, exhibiting heterogeneity (Li et al., 2023). However, a critical challenge lies in the capital goods nature of most green energy technologies (e.g., household PV, air-source heat pumps), characterized by "high upfront investment and low long-term operating costs". Within rural areas' underdeveloped credit markets, households commonly face severe liquidity constraints. Even when these technologies yield positive net present values over their lifecycles, substantial initial investments create insurmountable "entry barriers".

Second, price effects and energy substitution. Price effects influence farmer choices by altering the relative costs of different energy sources. For instance, rising coal prices prompt farmers to switch to alternative fuels like liquefied petroleum gas (LPG) or firewood, while electricity price changes significantly affect coal's share in energy consumption structures (Farsi et al., 2007; Liang et al., 2012).

Third, rebound effects and welfare improvements. Furthermore, the "rebound effect" resulting from energy efficiency gains manifests particularly complexly in rural contexts. Research has identified a "pre-rebound effect" among low-income households, indicating that savings from long-suppressed energy service demands (e.g., maintaining indoor temperatures at 16˚C in winter to save money) or efficiency improvements (e.g., installing energy-efficient air conditioners) do not directly translate into overall energy savings. Instead, these savings are primarily used to compensate for previously suppressed welfare.maintaining indoor temperatures at 16˚C during winter), the savings from efficiency improvements (e.g., installing energy-efficient air conditioners) do not directly translate into overall energy savings. Instead, these savings are first used to compensate for previously suppressed welfare gaps (e.g., raising indoor temperatures to a more comfortable 20˚C) (Aydin, 2023). This finding cautions that in the early stages of promoting rural green energy consumption, policy effects may manifest more as welfare improvements rather than absolute reductions in energy consumption. Macro evidence from Africa corroborates this phenomenon: research indicates that while financial inclusion drives economic growth, it is also associated with higher energy consumption and carbon emissions in the short term (Mukalayi & Inglesi-Lotz, 2023). This reflects the objective pattern where economic development releases suppressed energy demand.

Fourth, resource endowments and household characteristics. Factors such as resource endowments and household characteristics also constitute significant constraints on energy transition. First, infrastructure accessibility determines whether clean energy can reach rural households at reasonable costs, serving as a necessary material guarantee for energy transition. Transportation networks and grid coverage form the physical foundation of energy supply (Leach, 1992). In remote areas with weak infrastructure, the high cost of accessing clean energy often forces households to rely on locally available resources. Moreover, the greater the distance between villages and local markets, the higher the consumption of traditional biomass energy (Qiu et al., 2015). Second, socio-demographic factors influence energy choices by shaping cognitive levels and consumption preferences. Household heads with higher education levels are more inclined to choose clean energy. This stems partly from their greater economic capacity but is also closely linked to heightened environmental awareness and increased recognition of the health externalities associated with energy use (Liu, 2014). Furthermore, as women bear primary cooking responsibilities in rural households and experience indoor air pollution more directly, female heads of households often prioritize health and environmental factors in energy decisions, making them more inclined to adopt clean fuels like liquefied natural gas. Research examining demographic characteristics has also found that aging rates, household size, head of household age, per capita arable land area, and consumption preferences collectively influence energy choices (Wang et al., 2023a, 2023b; Fremstad et al., 2018).

2) Non-Economic Factors: Overlooked Decision Costs and Behavioral Biases

First, the "iceberg effect" of transaction costs. A large-scale randomized controlled trial (RCT) targeting low-income households in the United States revealed that a completely free, professionally audited energy-saving retrofit program capable of generating thousands of dollars in net household benefits achieved an actual participation rate of only 1% without additional incentives (Fowlie, Greenstone, & Wolfram, 2015). This compellingly demonstrates that "non-monetary costs"—or "transaction costs" within the Williamson framework—constitute a massive "iceberg" obstructing policy adoption. These costs specifically include: Search and information costs: Farmers struggle to effectively discern product quality and identify reliable service providers in a fragmented market. Administrative and procedural costs: Understanding complex policy terms, filling out cumbersome application forms, and engaging in multiple communications with government agencies and installers consume substantial time and effort—the so-called "hassle costs". Uncertainty costs: Skepticism about new technology performance, distrust of future energy savings, and concerns about the complexity of installation and maintenance processes. This phenomenon points directly to a theoretical flaw in the existing policy framework: policy design is overly based on the assumption of "perfect rationality", overlooking the costs of information search and uncertainty within transaction costs. Information empowerment is precisely the core means to address this flaw.

Second, cognitive limitations and behavioral biases. Beyond external transaction costs, behavioral biases stemming from individual cognitive limitations are equally significant. Farmers, like all ordinary individuals, exhibit bounded rationality in energy decision-making. This manifests as present bias (over-discounting future benefits), status quo bias (preference for maintaining the current situation), and limited capacity to process complex information. These behavioral factors collectively create a significant gap between the optimal decisions assumed by the "rational economic agent" model and actual behavior.

Overall, farmers' energy consumption behaviors exhibit considerable complexity. This complexity indicates that relying solely on economic incentives is unlikely to fundamentally alter their energy choices. The significance of digital rural development lies in its ability to systematically reshape farmers' payment capacity, consumption preferences, and decision-making literacy through multiple socioeconomic effects—including income growth, consumption upgrades, and capacity building. This provides a more comprehensive and sustainable driving force for energy structure transformation.

5. Socioeconomic Benefits of Digital Villages

The impact of digitalization on rural household energy consumption structures is largely achieved indirectly through its socioeconomic effects. These effects alter rural residents' income levels, influence shifts in consumption patterns, and reshape their cognitive abilities and behavioral logic. Together, they form a critical intermediary chain influencing energy consumption. Existing literature research can be broadly summarized in three aspects: income effects, consumption effects, and capacity building. These macro-level transformations collectively constitute the fundamental socioeconomic foundation upon which the transition of rural energy consumption relies.

1) Income Enhancement and Distribution Effects

Numerous empirical studies have confirmed that internet penetration and digital technology adoption promote income growth among farmers (Reuschke & Mason, 2020; Khan et al., 2022). These investigations indicate that the fundamental pathway for digital rural development to boost farmer incomes lies in accelerating rural digital transformation and expanding information access channels. Research by Ma et al. (2025) further contributes from the perspective of household innovation and entrepreneurship, demonstrating that information technology can alleviate credit constraints and lower entrepreneurial barriers, thereby boosting farmers' incomes. Additional studies have identified further mechanisms, including stimulating entrepreneurship, advancing digital finance penetration, and increasing the inflow of production factors (Li & Tong, 2025); easing information constraints; optimizing resource allocation; equalizing educational opportunities; and enhancing regional attractiveness (Klonner & Nolen, 2008; Synowiec, 2021). Notably, the income-boosting effects of digital villages exhibit complex distributional patterns, with more pronounced gains for low-income groups, unconnected farmers, and western regions. While this helps narrow intra-group disparities, higher-educated individuals derive greater benefits, potentially widening gaps. Overall, this presents a dual characteristic of "pro-poor effects" coexisting with the "Matthew effect". Furthermore, the head of household's education level exerts a positive moderating effect, while age exhibits a nonlinear threshold characteristic (Zhang et al., 2025). Additionally, digital finance facilitates remittance and payment services for rural residents, enabling low-income groups to access more financial services (Munyegera et al., 2016). Collectively, these findings indicate that the economic empowerment effects of digital finance in rural areas are unevenly distributed. The income gains it generates lay the foundation for households' ability to afford energy consumption upgrades. However, the extent to which this foundation is solidified varies across groups and regions, setting the stage for understanding subsequent differences in energy outcomes. Overall, the universal improvement and differentiated enhancement of residents' purchasing power provide the most fundamental economic prerequisite for households to pursue any form of consumption upgrading, including energy consumption.

2) Consumption Upgrading and Structural Transformation

In driving rural income growth, digital village initiatives have demonstrated a notably pronounced pull effect on rural consumption, particularly in discretionary spending (Si & Shi, 2024). The digital transformation of rural infrastructure and daily life serves as the key driver of this effect. Its underlying mechanism involves digital village development, directly creating novel consumption scenarios. Moreover, it indirectly unleashes consumption potential by altering income structures and alleviating consumption constraints. A survey conducted in Zhejiang's digital village pilot areas revealed the underlying transmission mechanism. The study found that digital village development promotes the upgrading of rural residents' consumption structures and the improvement of consumption habits. However, this effect is not achieved directly but through increases in wage income, property income, and total income. In other words, income serves as a crucial intermediary role. More profoundly, scholars identified "digital literacy" as a key latent variable mediating pathway. This clearly demonstrates the intrinsic logic from "digital access" to "capability enhancement" and ultimately to "behavioral change" (Zhang & Ma, 2022). Regarding specific pathways, digital industrial integration drives consumption upgrading by creating jobs, while digital finance promotes it by enhancing payment convenience (Liu et al., 2025). Concurrently, it relies on advancing insurance innovation and improving service delivery to increase household insurance coverage. This mitigates long-term income shocks, shares risks, and reduces precautionary savings—the easing of precautionary constraints directly boosts household consumption (Bacchetta et al., 1997). Furthermore, mobile money applications reduce transaction costs, increase income, mitigate risks associated with traditional savings and remittances, and address liquidity constraints. Consumption upgrading—particularly the pursuit of higher-quality, convenient lifestyle services—inherently implies demand for cleaner, more efficient, and reliable energy, thereby providing powerful demand-side traction for energy consumption structure transformation. This widespread pursuit of higher-quality and more convenient lives constitutes an endogenous demand driver for all modern consumer goods markets, including energy services, fostering the modernization of consumption structures from a conceptual perspective.

3) Digital Capacity Building and Literacy Development

The core principle of digital empowerment lies in "empowering people". Existing research generally agrees that digital rural development can enhance farmers' internet usage capabilities and digital literacy, which form the very foundation for realizing and translating digital dividends into tangible actions. The formation and improvement of farmers' digital literacy constitute a multi-level, systemic process encompassing individuals, organizations, and institutions. One study, based on case research of agri-entrepreneur organizations, proposed a three-stage model for the formation of high-quality farmers' digital skills: initial adaptation, breakthrough transformation, and generative development (Chen & Shi, 2025). This model illustrates that digital skills are not acquired in isolation but are gradually built into a complete digital "skill stack" within organized communities of practice, driven by division of labor, resource sharing, and a shared vision. Other studies focus on practical challenges, comprehensively analyzing obstacles in cultivating farmers' digital literacy. These challenges are divided into internal and external factors. Internally, constraints include age structure, educational attainment, and traditional mindsets. Externally, challenges stem from weak information infrastructure, insufficient digital device availability, limited applicable scenarios, and the absence of lifelong education and training systems (Liu & Huang, 2025). These inherent digital capability disparities among farmers directly impact their ability to leverage digital technologies for accessing energy information. They also affect their capacity to evaluate the cost-effectiveness and health/environmental impacts of different energy sources, as well as their ability to make informed decisions and take action. Higher digital literacy translates to stronger information filtering capabilities and more rational cost-benefit awareness. It also lowers the threshold for adopting new technologies, thereby tangibly enhancing farmers' agency in energy consumption transformation. The cultivation of digital literacy essentially reshapes individuals' initiative, determining whether and how farmers can utilize new economic conditions and market information to proactively make optimized life decisions and become active participants rather than passive recipients of transformation.

In summary, through promoting income growth, driving consumption upgrading, and empowering individuals, digital village construction has profoundly transformed rural socioeconomic ecosystems and residents' behavioral logic. These macro-level socioeconomic benefits collectively form a backdrop for profound rural transformation. Against this backdrop, the transition of rural households' energy consumption has gained economic feasibility, demand-driven inevitability, and individual initiative. However, how these macro conditions are specifically and systematically translated into rural households' actual energy consumption behaviors requires an in-depth examination of the micro-level mechanisms constructed by digital technologies—specifically, a multi-channel, interconnected network of effects directly woven by digital technology—to understand how these macro-level shifts can be precisely channeled toward green, efficient energy consumption behaviors.

6. The Effect Network of Digital Technology on Energy Consumption

As discussed in the previous chapter, digital village construction has created macro socioeconomic conditions for the transition of rural energy consumption. This chapter further reveals that digital technology itself, as a set of tools and platforms, directly acts on the energy decision-making and behavioral links of rural households through constructing a three-dimensional effect network, converting macro conditions into micro actions. This network is primarily realized through the following five interconnected and mutually reinforcing enabling channels.

First, economic empowerment represents a prerequisite pathway. Digital villages enhance household income and wealth levels by promoting non-agricultural employment, entrepreneurship, and inclusive finance (Ma et al., 2025; Zhou et al., 2025; Zhang et al., 2025). Improved payment capacity fundamentally alleviates the budget constraints associated with clean energy adoption. Clean energy typically involves higher initial investment costs and relatively higher energy prices. Enhanced affordability enables households to "climb" the energy ladder, transitioning from reliance on traditional solid fuels to cleaner, more efficient modern energy sources. This channel directly inherits the macro effect of income growth discussed in previous chapter, materializing it into immediate economic tools covering credit, payment, and income-generation links, thereby providing direct financial support and liquidity solutions for rural households when making energy procurement decisions. Economic empowerment represents a "foundational support" approach rather than a "fundamental" solution—it addresses the question of "can they afford it?" but fails to resolve the core contradiction of "are they willing to buy?" Its effectiveness hinges on information empowerment, activating the willingness to make purchasing decisions.

Second, information empowerment represents digital technology's most fundamental contribution. Its fundamental nature lies in the following: even if farmers possess the economic means to pay, they will remain entrenched in traditional energy consumption patterns without information empowerment to break down cognitive barriers and alleviate risk concerns. Conversely, with sufficient and credible information, even farmers with limited incomes may overcome economic constraints through credit facilities or installment plans. Tools like the internet, e-commerce platforms, and social media substantially reduce information search costs and asymmetry (Jensen, 2007). This encompasses information on clean energy equipment performance, pricing, subsidy policies, usage benefits, and market suppliers. Transparent information enhances farmers' understanding of the marginal utility of clean energy (Wu et al., 2025), altering their preference functions and effectively stimulating latent demand for green energy. Independent of macro income growth, this channel directly acts on rural households' cognition and preferences by reducing information barriers, serving as a key technical pathway to stimulate their intrinsic green demand and guide informed decision-making.

Third, the infrastructure synergy channel demonstrates the effects arising from the integration of digital infrastructure and energy infrastructure. Broadband networks and mobile communications form the foundational conditions for the operation of energy internet, smart grids, and distributed energy management systems. The development of digital villages has significantly enhanced the synergy of these energy system networks through broadband and mobile communications (Guo & Zhou, 2025). This synergy improves the accessibility of clean energy services in remote areas (Zhang et al., 2023b) and may leverage intelligent management to reduce energy losses and usage costs, thereby enhancing the stability, convenience, and affordability of clean energy adoption. This channel concretizes the hardware foundation underlying consumption upgrading discussed earlier. Through the physical integration of "digital-energy" infrastructure, it directly lowers the threshold for clean energy use in terms of accessibility, cost, and efficiency.

Fourth, social network diffusion channels leverage digital technologies to activate and amplify pre-existing social networks in rural areas. Through digital media such as WeChat groups and short-video platforms, experiences, evaluations, and demonstrations related to clean energy use can spread rapidly. This dissemination occurs among neighbors and friends, creating a powerful "peer effect" and social normative pressure. (Bollinger & Gillingham, 2012; He et al., 2022b). This socialized promotion method, grounded in trust among acquaintances, generally reduces the perceived risks and uncertainties associated with adopting new technologies more effectively than traditional commercial advertising. This channel deepens the social learning dimension of capacity building discussed in previous chapter, focusing on the viral spread of energy-related topics within acquaintance networks. It utilizes trust mechanisms to directly reduce the perceived risks of new technologies and accelerate adoption processes.

Fifth, the capacity-building channel ensures the sustainability and longevity of the aforementioned enabling channels. The ultimate goal of digital rural development lies in enhancing farmers' digital survival and development capabilities—that is, digital literacy. Farmers with higher digital literacy can more proactively and effectively leverage economic, informational, and social network channels to become active decision-makers and early adopters in energy transition (Zhao et al., 2022). This channel directly corresponds to the individual empowerment discussed in earlier. Here, digital literacy is regarded as the "operating system" driving the effective operation of all other channels, determining the depth and efficiency with which rural households utilize technical tools to address energy issues.

These five pathways do not operate in isolation; they are interwoven and mutually reinforcing. These pathways collectively influence rural households. They systematically alter the budget constraints, information aggregation, technology accessibility, social norms, and individual capabilities households face, driving the energy consumption structure toward cleaner, more efficient, and modernized patterns from high-pollution, low-efficiency traditional models. For example, a rural household may learn about solar PV installation through social network channels (information stimulation), compare prices and understand subsidy details via e-commerce platforms (information empowerment), secure financing through digital financial products or use funds accumulated from digital economic activities (economic empowerment), and achieve efficient management through integrated infrastructure such as smart meters (infrastructure synergy)—all processes supported by their digital literacy (capacity building). This multi-channel linkage constitutes a complete, dynamic, and systematic micro-level picture of digital technology-driven energy consumption transformation.

Critically, the five enabling pathways delineated above can be mapped onto the three binding constraints identified by the "Energy Ladder" framework in Section 2—namely, energy "availability", "affordability", and "reliability" (Kaygusuz, 2011). The affordability constraint is addressed most directly by the economic empowerment pathway: digital finance instruments such as pay-as-you-go (PAYG) models decompose the high upfront costs characteristic of modern energy equipment into small, recurring payments, thereby relaxing the liquidity barriers that the standard energy ladder model attributes solely to aggregate income levels. The availability constraint is jointly relaxed by the infrastructure synergy and information empowerment pathways: broadband-enabled distributed energy management systems extend the physical reach of clean energy services into under-served rural areas, while digital platforms and e-commerce channels substantially reduce the search and transaction costs that previously rendered modern energy options inaccessible. The reliability constraint—fundamentally a perceptual barrier rooted in uncertainty about unfamiliar technologies—is addressed by the social network diffusion pathway, through which locally verified peer experiences transmitted via digital media reduce perceived adoption risk more effectively than impersonal technical documentation. The capacity-building pathway reinforces this channel by equipping farmers with the evaluative literacy necessary to independently assess the long-term cost-benefit profiles of modern energy options. Viewed holistically, these five pathways do not merely replicate the income-driven ladder-climbing mechanism of classical energy transition theory; rather, they constitute a qualitatively distinct set of channels through which digital village development actively dismantles the institutional, informational, and perceptual frictions that cause households to remain trapped at lower rungs of the energy ladder.

7. Digital Technology-Based Policy Intervention Strategies

Drawing on behavioral economics and new institutional economics, this paper constructs a three-dimensional "structure-cognition-feedback" intervention framework to systematically analyze how digital rural development drives green energy consumption among farmers. This framework is grounded in the theory that individual energy consumption decisions are constrained by three levels: the external decision environment (budget constraints, institutional arrangements, market structures), internal cognitive states (information sets, risk preferences, behavioral intentions), and behavioral consequence feedback (immediate utility, social recognition, learning reinforcement). Traditional policies often focus on single-dimensional interventions. The revolutionary value of digital technology lies in its ability to simultaneously leverage all three dimensions and create synergistic effects, thereby systematically overcoming the multiple challenges faced by traditional policies in rural contexts: high transaction costs, low information dissemination, and weak feedback mechanisms. The fundamental flaw in the existing policy framework lies in its erroneous theoretical premise that "farmers are perfectly rational economic agents". It relies excessively on single-dimensional interventions centered solely on economic incentives, neglecting non-economic constraints such as cognitive biases and information barriers. This has led policies into a dilemma of "high input, low output".

Specifically: Structural interventions directly influence the boundary conditions of rational choice by altering economic parameters (prices, costs, constraints) within the decision-making environment. Preemptive interventions act at the decision front-end, reshaping individuals' cognitive schemas and behavioral intentions through information provision and goal setting. Consequential interventions leverage post-behavioral feedback reinforcement mechanisms, shaping long-term habits through instant rewards/punishments and social comparison. Digital technology's empowerment across each dimension represents not merely enhanced tool efficiency but a paradigm shift in intervention logic.

1) Structural Interventions: Correcting Market Failures and Reconstructing Decision Environments

The economic rationale for structural intervention originates in diagnosing market failures. The positive externalities of green energy technologies—environmental benefits and carbon reduction effects—cannot be fully reflected through market pricing mechanisms, leading to private investment levels that are systematically below the socially optimal. Government intervention through structural tools like pricing policies, fiscal subsidies, and mandatory standards essentially "internalizes" these externalities, aligning individual cost-benefit calculations toward maximizing social welfare. Digital technology's role in this process extends beyond reducing policy implementation costs; it creates new intervention possibilities—rendering policy tools previously unfeasible due to information asymmetry and excessive oversight costs now viable. The core flaw in existing structural intervention policies lies in simplifying farmer decision-making to a rational "cost-benefit" calculation, overlooking the dominant role of cognitive biases in decision-making. Even when subsidies reduce economic costs, farmers may still refuse participation if they question the effectiveness of the technology due to insufficient information.

First, Demand-Side Management and Demand Response: From Passive Adjustment to Active Participation. Demand-Side Management (DSM) and Demand Response (DR) represent a shift in energy governance paradigms from "supply-oriented" to "demand optimization". Traditional energy system planning focused on meeting peak demand by expanding power generation capacity to address load fluctuations, leading to significant investment wastage and resource idleness. The core concept of DSM is to optimize overall system efficiency by actively adjusting demand to shave peaks and fill valleys. The theoretical foundation of demand response programs traces back to time-differentiated pricing theory: when electricity prices fluctuate in real-time based on supply-demand conditions (e.g., peak-off-peak pricing, real-time pricing), rational consumers will adjust their usage patterns to maximize personal utility. Based on this logic, DR programs fall into two main categories: price-based demand response uses differentiated pricing mechanisms (e.g., time-of-use rates, critical peak pricing) to guide consumers in proactively adjusting their load curves; incentive-based demand response involves users entering agreements with operators to commit to reducing electricity consumption during specific periods in exchange for corresponding financial compensation. However, this mechanism faces dual challenges in rural contexts: First, farmers' responsiveness to price signals is constrained by rigid production and living requirements (e.g., seasonal irrigation needs, environmental control demands for livestock), making flexible adjustments difficult. Second, the absence of real-time metering and feedback mechanisms prevents price signals from effectively reaching micro-level decision-making. Digital technology fundamentally transforms this landscape: smart meters enable precise metering and real-time monitoring of electricity usage, mobile applications translate complex pricing information into intuitive decision-making guidance, and IoT devices (such as smart thermostats and automated irrigation systems) shift load adjustment from "manual response" to "automated optimization". Crucially, a substantial share of rural electricity demand in fact comprises loads that are temporally flexible and hence amenable to demand response coordination. Irrigation pumps—among the single largest categories of electricity consumption in China's water-intensive farming regions—operate within time windows defined by cumulative crop water requirements rather than instantaneous scheduling constraints, rendering them natural candidates for off-peak dispatch (Liu et al., 2018). Cold storage facilities for perishable agricultural outputs possess considerable thermal inertia, permitting short load interruptions without material deviation in storage temperature. Greenhouse supplemental lighting, grain-drying equipment, and domestic electric water heaters similarly admit flexible scheduling across disjoint time periods. When aggregated through IoT-enabled load controllers, these dispersed flexible loads constitute a meaningful and operationally viable demand response resource pool, substantiating the feasibility of rural DR programs beyond the purely theoretical level. This not only significantly reduces participation costs for farmers but also transforms DR from a "privilege" reserved for a few large users into an inclusive mechanism accessible to the broader farming community.

Second, fiscal subsidies and tax incentives: From cost-sharing to risk-sharing. The theoretical basis for fiscal subsidies and tax incentive policies lies in overcoming capital market imperfections: Green energy technologies typically feature "high initial investment, long payback periods, and uncertain returns". This makes risk-averse farmers likely to forgo investment due to liquidity constraints or risk premiums, even when the expected net present value is positive. Government intervention through fiscal tools essentially redistributes investment risks and returns between the private and public sectors. Examining the operational mechanisms of these policy instruments reveals three distinct types: First, direct cost-sharing mechanisms (e.g., direct grants, subsidies): These directly reduce the absolute investment amount, alleviating capital constraints. This approach is most effective for low-income farmers facing severe liquidity constraints, as even promising long-term returns may be blocked by immediate funding gaps. Second, intertemporal profit redistribution (e.g., tax credits, depreciation incentives): These allow investors to recoup initial investments through tax reductions over subsequent years, essentially front-loading long-term profits to reduce the time cost of capital. This tool is better suited for middle-to-high-income farmers or agribusinesses with stable tax bases. Third, risk-sharing mechanisms (e.g., interest-subsidized loans, government guarantees): These reduce capital costs by improving financing conditions, targeting groups with lower risk tolerance but adequate repayment capacity. European practices provide substantial empirical support for this classification framework. For instance, Italy's tax credit policy (2007-) enables households to deduct 55% - 65% of energy-efficient renovation expenditures over 5 - 10 years, essentially employing an intertemporal income redistribution mechanism. Hungary's "Warmth of the Home Programme" targets low-income households with upfront direct subsidies, substituting intertemporal tax incentives with immediate financial support. Spain's State Housing Plan employs a hybrid toolkit, matching subsidy methods to household income and housing type (Trotta, Spangenberg, & Lorek, 2018). The common logic underlying these differentiated designs lies in precisely identifying the primary constraint type for target groups (absolute funding gap vs. high financing costs vs. excessive risk premiums) and then matching corresponding policy tools to maximize marginal intervention efficiency. However, non-monetary costs may significantly diminish the effectiveness of economic incentives. A study of a fully subsidized (100% cost-free) residential energy efficiency retrofit program found extremely low household participation rates despite the absence of monetary costs (Fowlie, Greenstone, & Wolfram, 2015). This highlights the critical role of "hassle costs"—the complexity of application processes, information search costs, time and effort invested in coordinating with contractors, and inconvenience endured during construction. These hidden costs form invisible barriers to policy effectiveness. Digital technology offers a revolutionary solution to this dilemma: online platforms integrate the entire process—from information dissemination and eligibility verification to subsidy applications and progress tracking—reducing multiple trips to government offices and cumbersome paperwork to a single click. Digital service provider matching mechanisms lower search costs for farmers and contractors. Blockchain technology can even enable automatic subsidy calculation and instant disbursement. From a new institutional economics perspective, this constitutes an order-of-magnitude reduction in transaction costs—rendering policy instruments previously unfeasible due to excessive transaction costs now viable, thereby significantly expanding the scope for public policy intervention.

Third, regulations, standards, and mandatory requirements: the technical foundation for policy coordination. Mandatory energy efficiency standards, particularly building codes, represent a "non-price" structural intervention. Their theoretical logic lies in establishing minimum energy efficiency thresholds through legal enforcement, directly phasing out inefficient technologies and overcoming "adverse selection" (where low-quality products crowd out high-quality ones under information asymmetry). However, the effectiveness of regulatory policies heavily depends on the coordination of supporting mechanisms. Research indicates that the energy-saving effects of building codes are only significant in residential buildings equipped with central heating systems (Aydin, 2023). The underlying mechanism is that supporting regulations require such buildings to install individual meters, thereby transforming abstract building energy efficiency standards into economic signals directly perceptible to each household ("pay for what you use"). Conversely, in buildings using cost-sharing arrangements, the marginal costs and benefits of energy savings become obscured, rendering regulatory policies nearly ineffective. This underscores the critical importance of policy synergy: structural interventions must be combined with mechanisms that provide clear individual incentives to achieve full effectiveness. Simultaneously, smart metering technology plays a foundational role in this context. Traditional mechanical meters only record total electricity consumption without distinguishing usage by time or purpose, preventing the effective transmission of refined price signals (e.g., time-of-use pricing). Smart meters, through real-time, itemized metering, not only provide the technical foundation for demand response but also offer oversight tools for enforcing regulatory standards—transforming energy consumption from "unobservable" to "precisely controllable" and enabling the coordinated implementation of diverse policy instruments.

Finally, the existence of the rebound effect necessitates that policy evaluations extend beyond technical energy-saving potential. Improved energy efficiency reduces the effective price of energy services, potentially inducing users to increase consumption and partially offsetting energy savings (Aydin et al., 2017). More complex is the "pre-rebound effect": low-income and energy-poor households, constrained by budgets, initially consume far below levels necessary for comfort and health. After efficiency improvements, they tend to prioritize quality-of-life enhancements over reducing total energy consumption (Aydin, 2023). This finding offers profound implications for green energy policies targeting rural households: policy effectiveness may first manifest as welfare improvements rather than reductions in total energy consumption. Consequently, policy evaluation frameworks must incorporate both "energy efficiency gains" and "welfare improvements" as dual dimensions, avoiding the sole reliance on energy consumption reduction as the sole measure of success.

2) Preemptive Interventions: From Information Provision to Cognitive Reshaping

Unlike structural interventions that directly alter external constraints, proactive interventions operate along the causal chain of "cognition-intention-behavior". They indirectly guide behavioral choices by influencing the information set, belief systems, and goal setting at the decision-making front end. Its theoretical foundation traces back to the Theory of Planned Behavior: individual actions are determined by behavioral intentions, which are governed by three factors—behavioral attitudes (evaluation of consequences), subjective norms (expectations of significant others), and perceived behavioral control (self-assessment of execution capabilities). The core of proactive intervention lies in altering behavioral trajectories at the decision-making starting point by: optimizing behavioral attitudes through information provision, activating subjective norms via social norms, and enhancing perceived behavioral control through skill training. This is precisely the core pathway to correcting the theoretical shortcomings of the existing policy framework: reshaping farmers' cognition through information empowerment to compensate for decision-making biases caused by "bounded rationality". Its significance far exceeds that of mere economic incentives.

Within the framework of digital rural development, information and communication technologies (ICT) and digital platforms serve not only as conduits for information dissemination but also as foundational infrastructure for cognitive restructuring. They transform one-way information delivery into two-way interactive learning, static knowledge transfer into dynamic capacity building, and isolated individual decision-making into collaborative community action.

First, information provision: From eliminating asymmetry to optimizing cognition. Traditional information interventions are grounded in the theory of information asymmetry: farmers systematically underestimate the value of green energy technologies—such as solar PV and biogas—due to lacking critical information about their costs, benefits, and operational complexity, thereby forgoing potentially profitable investments. However, merely providing information does not necessarily drive behavioral change—information must be delivered in the right format, at the right time, and through credible channels to effectively inform decision-making. The Technology Acceptance Model (TAM) identifies "perceived usefulness" and "perceived ease of use" as critical drivers of technology adoption. When farmers can conveniently access information via digital platforms—such as installation costs, expected returns, maintenance methods, and local success stories for green energy technologies (e.g., solar PV, biogas systems)—their willingness to adopt significantly increases (Chowdhury & Islam, 2015). The empowerment of digital technology manifests across three progressive levels: Level One: The Revolution of Information Accessibility. Traditional outreach relied on government field visits and poster campaigns, resulting in limited coverage and poor timeliness. Smartphone apps, online communities, and digital "Energy User Associations" reduce information delivery costs to near zero while enabling real-time updates. Crucially, community mechanisms transform external policy promotion into internal experience sharing and peer learning, enhancing information credibility and persuasiveness (Geng & Xue, 2022). Second Layer: Establishing Feedback Mechanisms. Unlike one-way information dissemination, digital tools like smart meters provide dynamic, personalized real-time feedback. They enable farmers to monitor energy usage and costs instantly while offering customized energy-saving recommendations through data analysis, transforming abstract "energy conservation" into concrete actionable lists (Tanoto, 2024). Research confirms that households equipped with smart meters reduce energy consumption by 15% (Du, Han, & de Vries, 2022). This immediate feedback loop makes the outcomes of energy-saving behaviors instantly visible, thereby reinforcing the positive cognitive-behavioral association. Third Layer: Compressing the Learning Curve. Digital agriculture (Agriculture 4.0) embeds complex technical knowledge into automated equipment through sensors, data analytics, and decision support systems. Farmers can achieve precision irrigation and smart fertilization with simple operations without requiring deep specialized knowledge, significantly lowering the cognitive barrier to technology adoption.

However, the digital divide may paradoxically exacerbate inequalities through information interventions. Many rural communities face constraints from inadequate network connectivity, weak digital infrastructure, and low digital literacy (Chowdhury & Islam, 2015; Samsudin et al., 2024). In sub-Saharan Africa, only about 42% of rural households have stable mobile internet access, and less than 25% of farmers in some agricultural communities can effectively use AI-driven tools (Chowdhury & Islam, 2015). This implies that any digital information intervention must be synchronized with infrastructure development and digital literacy programs. Otherwise, it risks widening the gap between the "information haves" and "information have-nots" rather than bridging information asymmetries.

Second, goal-setting and commitment mechanisms: activating self-regulation systems. Goal-Setting Theory reveals a key mechanism: clear, specific, and moderately challenging goals activate individuals' self-regulation systems, driving sustained behavior through a "goal-action-feedback" loop. In energy consumption, this manifests as setting concrete energy-saving targets (e.g., "Reduce monthly electricity usage by 10%") and monitoring progress through regular feedback. Digital platforms enhance this mechanism in two ways: First, personalized and dynamically adjusted goals. Energy management apps can recommend challenging yet achievable targets based on user history, household characteristics, and seasonal variations, while gamification elements (progress bars, virtual badges, leaderboards) boost engagement. When combined with social norms (e.g., "neighborhood comparisons"), this activates social recognition psychology, further strengthening commitment to goals. Second, the socialization and visualization of commitments. Commitment mechanisms increase action probability by leveraging the principle of "cognitive dissonance" (psychological discomfort caused by inconsistency between words and actions) through public or private declarations of intent. At the community level, public collective energy-saving commitments (e.g., village "energy-saving challenges") leverage community cohesion and peer monitoring to create soft constraints (Clausen & Rudolph, 2020). Digital platforms (social media, village WeChat groups) minimize the organizational costs of such commitments while amplifying social influence through visual displays (e.g., real-time rankings of energy-saving progress).

3) Consequential Interventions: Habit Formation through Reinforced Feedback

The theoretical foundation of consequential interventions stems from operant conditioning theory: whether a behavior persists depends on its consequences—positive consequences (rewards, positive feedback) increase the probability of repetition, while negative consequences (punishment, negative feedback) inhibit it. In the energy consumption domain, this translates to a core proposition: if farmers can immediately and clearly perceive the positive consequences of energy-saving behaviors (electricity bill savings, social recognition, environmental contributions), these actions are more likely to solidify into long-term habits. Digital technology plays a pivotal role here by transforming inherently delayed and ambiguous consequence feedback into instant, precise, and multidimensional reinforcement signals.

First, the feedback mechanism: From Invisible to Visual. A fundamental issue with traditional energy consumption is its invisibility: a time lag (typically one month) exists between electricity usage and bill payment, and monthly statements only show total consumption without breaking it down by appliance or time period. This blurred causal chain makes it difficult for energy-saving behaviors to receive immediate reinforcement, hindering the formation of stable habits. Specifically, digital feedback mechanisms address this challenge across three dimensions: First, the temporal dimension: shifting from lag to real-time. Smart meters and Home Energy Reports (HERs) reduce energy consumption data update cycles from "monthly" to "real-time". Through in-home displays or mobile apps, households can instantly observe how actions like turning off idle appliances or adjusting air conditioner temperatures affect energy consumption. This immediate visibility drastically shortens the "behavior-consequence" feedback loop, maximizing reinforcement effects (Composto & Weber, 2022). Second, granularity dimension: From aggregate to itemized. Traditional bills only show total electricity consumption, while digital systems can break it down to appliance-level, time-of-day-level, or even function-level (e.g., proportions for lighting, cooling, heating). This enables households to precisely identify "energy hogs" and take targeted measures. Such granular feedback transforms vague energy-saving goals into concrete action lists. Third, social dimension: From individual to comparative. Social comparison theory suggests that individuals evaluate their performance by benchmarking against others. The OPOWER project demonstrated the power of "neighborhood comparison" (comparative feedback): contrasting household energy consumption with similar groups ("neighbors") activates social recognition motivation, gently nudging high-consumption users toward average levels. However, caution is warranted against the "boomerang effect"—where previously energy-efficient households may increase consumption upon discovering they fall below average (Bahinipati, Sirohi, & Rao, 2022). The countermeasure is to incorporate "injunctive messages" (e.g., smiley symbols) to explicitly convey social expectations and reinforce the legitimacy of energy-saving behaviors (Composto & Weber, 2022).

Second, incentive rewards: shifting from extrinsic motivation to intrinsic drive. Reward mechanism design faces a core tension: balancing external incentives with intrinsic motivation. Self-Determination Theory suggests that excessive external rewards may "crowd out" intrinsic motivation (e.g., environmental awareness, social responsibility), causing behaviors to disappear once rewards cease. Empirical studies validate this mechanism: when households receive both informational and monetary incentives, energy savings decline compared to information-only interventions, suggesting monetary rewards diminish non-price interventions' effectiveness (Sudarshan, 2017; Composto & Weber, 2022). Overcoming this dilemma requires refined incentive design: First, the rise of non-monetary rewards. Compared to direct monetary incentives, non-monetary rewards based on social recognition and gamification demonstrate greater sustainability. By linking energy-saving behaviors to intrinsic psychological needs like honor and belonging—through methods such as publishing "energy-saving leaderboards" via apps, awarding virtual badges, or organizing community competitions—longer-lasting intrinsic motivation can be stimulated (Sridhar et al., 2023). The advantage of such incentives lies in their ability to reinforce environmental identity through social validation rather than crowding out intrinsic motivation. Second, integration with market mechanisms. At the macro level, incentives can be embedded within energy market designs. Smart grid demand response mechanisms allow users to reduce electricity consumption during peak hours and receive compensation—essentially personalizing market price signals. The roadmap for agriculture-clean energy coupling systems further expands this approach: guiding smart agriculture with flexible loads (e.g., dispatchable irrigation, greenhouse supplemental lighting) to participate in grid peak shaving, absorbing surplus clean energy, and achieving mutual benefits for farmers and the grid (Liu et al., 2018). This design transforms incentives from "exogenous" to "endogenous"—farmers conserve energy not for subsidies but naturally contribute to the system while optimizing their own production schedules.

8. Research Summary and Future Outlook

1) Core Findings: The Three-Tiered Progression of Digital Technology Empowerment

This paper systematically addresses the core question of "how digital rural development drives farmers' green energy consumption" using an analytical framework grounded in new institutional economics and technology-enabled theory. Findings reveal that digital technology transcends traditional policy interventions not through singular tool improvements, but through a three-tiered paradigm shift:

Tier One: Reducing Institutional Transaction Costs—From Difficult Implementation to Widespread Accessibility

The implementation challenges of traditional policies in rural areas stem from the dual constraints revealed by Williamson's transaction cost framework: farmers' "bounded rationality" (difficulty processing complex information) and "opportunism" in policy execution (rent-seeking and inefficiency caused by information asymmetry). Digital platforms integrate information flows, approval processes, and service delivery online, reducing the information search costs, administrative coordination costs, and supervision costs of policy implementation by an order of magnitude. Specific mechanisms include:

- Deregulation of information access: Transitioning from "multiple trips to government offices" to "one-click online queries", reducing information search time from days to minutes;
- Automated process approvals: Blockchain-based eligibility verification and smart contract subsidy disbursement eliminate rent-seeking opportunities and time costs associated with manual reviews;
- Platform-based service matching: Digital supplier evaluations and intelligent recommendation systems reduce search and matching costs for farmers and service providers.

Second Layer: Reconstructing Resource Allocation Mechanisms—From Administrative Allocation to Market Coordination

The integration of digital financial innovations (such as PAYG models) with smart metering technology represents not merely an improvement in payment methods and measurement tools, but a profound shift in resource allocation logic:

- PAYG's risk redistribution mechanism: By breaking down large lump-sum payments into small, ongoing installments, it fundamentally shifts investment risk from farmers (who previously bore all upfront risk) to a dynamic sharing between suppliers and consumers. This not only alleviates liquidity constraints but also enables real-time alignment between payments and services through the "pay-as-you-go" mechanism, reducing default risk.
- Signal Transmission Function of Smart Meters: Transforming energy consumption from "unobservable" to "precisely controllable", it provides the technical foundation for market-based mechanisms like demand response and time-of-use pricing. Crucially, it enables price signals to effectively reach micro-level decision-making, converting abstract market supply-demand dynamics into tangible economic incentives for farmers.
- Technological foundation for policy coordination: Smart metering serves not just individual policy tools but enables coordinated implementation of diverse policies—demand response requires real-time measurement, fiscal subsidies demand precise accounting, and regulatory enforcement necessitates dynamic oversight. These formerly isolated policies now form a synergistic whole through digital technology.

Third Layer: Shaping New Subject Relationships—From Passive Recipient to Active Participant

- From "Policy Recipients" to "System Participants": The traditional unidirectional "government-farmer" empowerment relationship evolves into a multifaceted interactive network of "platform-community-individual". Digital platforms serve not only as policy delivery channels but also as public spaces where farmers express needs, share experiences, and coordinate actions. Community mechanisms transform external promotion into endogenous motivation, shifting policy implementation from "top-down" to "two-way interaction".

- From "Consumers" to "Prosumers": The integration of distributed energy (e.g., household PV) with smart grids empowers farmers to simultaneously act as energy producers, consumers, and traders. This not only generates economic benefits (electricity sales revenue, demand response compensation) but more importantly, enhances farmers' agency—shifting them from passive recipients of energy services to active participants in optimizing energy systems. The core driving force behind this transformation in the principal-agent relationship lies in the cognitive awakening and capability enhancement enabled by information empowerment. Farmers have shifted from "passively receiving economic subsidies" to "actively participating in the energy transition". At its essence, information empowerment corrects the limitations of "bounded rationality", ultimately demonstrating why it holds a more fundamental significance than economic empowerment.

2) Research Outlook

While existing research has laid the groundwork for understanding the relationship between digital villages and green energy consumption, significant knowledge gaps remain. Future research urgently needs to deepen in the following directions, which are intrinsically interconnected:

First, Causal Identification and Mechanism Testing: Moving from Correlation to Causation

A core limitation of current research lies in weak causal inference. Most studies remain at the level of correlation analysis (e.g., positive correlation between digital technology adoption and green energy uptake) or descriptive case studies, lacking rigorous identification of net effects and causal pathways. This undermines the reliability of policy recommendations—observed correlations may stem from omitted variables (e.g., regional economic development simultaneously influencing digitalization and energy consumption) rather than causation. Future research urgently requires more field experiments based on randomized controlled trials (RCTs), leveraging exogenous variation (e.g., randomly assigning subsidies or smart meters) to precisely identify the causal effects of specific interventions. For example: - Differentiated impacts of varied feedback interface designs (aggregate vs. itemized, textual vs. graphical) on energy-saving behaviors; - Effects of distinct PAYG contract terms (payment frequency, penalty clauses) on adoption rates and default rates; - Heterogeneous impacts of social comparison information framing (ranking vs. percentile) on high/low energy consumers. Only through rigorous causal identification can policy ROI be accurately assessed, preventing resource wastage. The core causal relationship requiring verification is whether the promotional effect of information empowerment on green energy consumption significantly exceeds that of economic empowerment, and whether it operates through the pathway of cognitive restructuring. This verification will directly support the controversial claim proposed in this paper.

Second, Heterogeneity Effects and Distributional Consequences: From Average Effects to Distribution Effects

Average Treatment Effect (ATE) obscures the heterogeneous impact of policies across groups. Digital interventions may significantly affect farmers with different incomes, ages, education levels, and digital literacy. Ignoring this could lead policies to exacerbate the "Matthew Effect" (the rich get richer, the poor get poorer) rather than reduce inequality. Future research should prioritize conditional ATE and quantile treatment effects to identify distributional patterns of policy impacts. Key questions include: Does the digital divide concentrate policy benefits among high-literacy groups? While low-income farmers face liquidity constraints making PAYG more essential, are they also more likely to be excluded due to digital skill gaps? How can "inclusive digitalization" strategies be designed to ensure vulnerable groups are not left behind? Such research holds not only academic value but also policy implications for social equity—if digitalization exacerbates inequality, it must be complemented by targeted capacity building and subsidized interventions.

Third, Data Governance and Market Design: From Technical Feasibility to Institutional Sustainability

Digitalization generates vast amounts of energy consumption data from farmers, which serves as both a valuable resource for optimizing energy allocation and a potential source of privacy breaches and power abuses. Current research overly focuses on technical aspects (how to collect and analyze data) while neglecting institutional dimensions (who owns data rights, how to prevent misuse, and how to distribute benefits). Future efforts should establish a normative framework for data governance, balancing efficiency with fairness and innovation with security. Core questions include: Defining data ownership—Who owns farmers' energy consumption data (individual farmers, platforms, or public goods)? How should benefit-sharing mechanisms (e.g., data dividends) be designed? Privacy protection mechanisms—how can individual privacy be safeguarded through technologies like differential privacy and federated learning while leveraging data to optimize energy allocation? Market rule design—how can "prosumers" be prevented from manipulating prices through information advantages in peer-to-peer (P2P) electricity trading? How should access mechanisms and penalty clauses be designed to ensure market stability? Such research requires interdisciplinary collaboration across economics, law, and computer science. The outcomes should extend beyond academic papers to deliver actionable policy guidelines and legal frameworks.

Fourth, Long-Term Effects and Behavioral Persistence: From Short-Term Impacts to Habit Formation

Existing research predominantly focuses on short-term evaluations (ranging from months to one or two years), with insufficient attention to long-term effects and behavioral persistence. The core question is: Can digital interventions foster habit formation, or do they merely induce temporary compliance (temporary behavioral adjustments)? Do behaviors rebound once subsidies are withdrawn or incentives cease?

Therefore, future research should employ long-term panel data and dynamic models (e.g., state-dependent models) to distinguish between interventions' immediate effects, sustained effects, and exit effects. Key questions include: Which intervention types are more likely to trigger habit formation (feedback vs. rewards, information vs. goal-setting)? What are the critical thresholds for habit formation (duration, repetition frequency)? How should "tapering" strategies be designed to prevent behavioral rebound from abrupt incentive termination? Such research is crucial for assessing policy sustainability—only interventions with long-term effectiveness warrant large-scale implementation.

Fifth, Interdisciplinary Integration: From Single Perspectives to Systems Theory

Farmers' energy consumption behavior constitutes a complex system of interacting factors: economic (income, price), psychological (cognition, attitudes), social (norms, networks), and technical (facilities, literacy) elements interplay. Current research predominantly adopts single-discipline perspectives (economics emphasizes price incentives, psychology highlights cognitive biases, sociology focuses on normative influences), failing to capture systemic complexity. Therefore, we should expedite the development of a multidisciplinary theoretical framework that organically integrates micro-behavioral theories (e.g., Theory of Planned Behavior), meso-social theories (e.g., Social Network Theory), and macro-institutional theories (e.g., New Institutional Economics). Specific directions include: developing Agent-Based Models (ABMs) to simulate interactive learning and technology diffusion within farmers' social networks; employing Structural Equation Modeling (SEM) to analyze causal chains among economic, psychological, and social variables; applying system dynamics to depict feedback loops and long-term evolution. Such research not only yields more precise policy recommendations but may also give rise to new theoretical paradigms—such as the "digitally empowered socio-technical-ecological systems" theory.

In summary, through in-depth exploration in these directions, academia can not only provide a more robust theoretical foundation and more precise policy recommendations for digital rural development and the green energy transition in rural areas, but also advance theoretical innovation—namely, developing a new paradigm of "digital sustainable transformation" that transcends the limitations of single disciplines and integrates the multidimensional aspects of technology, economy, society, and environment. This will contribute Chinese wisdom and solutions to the global fight against climate change and the achievement of Sustainable Development Goals. This embodies the ultimate mission of academic research: not only to explain the world, but to change it.

9. Literature Sources and Research Methodology

To ensure the systematic, objective, and academically rigorous nature of this review, the study strictly adheres to the research paradigm of systematic literature reviews. It conducts systematic retrieval, screening, and comprehensive analysis of research related to "digital rural development" and "green energy consumption by farming households".

Regarding literature retrieval, this study completed searches of major Chinese and international academic databases in April 2025. Chinese literature primarily utilized China National Knowledge Infrastructure (CNKI) as the core data source, focusing on CSSCI and CSCD-indexed journals. English literature covered international mainstream databases including Web of Science Core Collection, Scopus, and ScienceDirect. A combined strategy of subject terms and free-text keywords was employed. Chinese search terms included "数字乡村", "智慧乡村", "农村数字化转型", "农户能源消费", "清洁能源采纳", and "能源贫困". English search terms included "digital village", "rural digitalization", "household energy consumption", "clean energy transition", and "energy poverty". The search timeframe spanned January 2000 to March 2025 to ensure comprehensive coverage of the field's evolution from inception to development.

At the literature screening stage, this study established clear inclusion and exclusion criteria. Included studies must meet the following criteria: 1) Focus on rural areas and households in China or comparable contexts; 2) Explicitly examine the relationship between digital factors (e.g., internet, e-commerce, digital finance) and household energy consumption behavior, structure, or technology adoption; 3) Be empirical research, theoretical analysis, or systematic reviews; 4) Be published in peer-reviewed journals or high-quality academic publications. Exclusion criteria include: 1) Focus solely on macro-level energy policies or urban energy issues without addressing rural digitalization; 2) Non-research literature such as news reports or opinion pieces; 3) Literature for which full-text access was unavailable. The screening process was conducted independently by two researchers through three stages: initial screening (title and abstract review), full-text rescreening, and resolution of discrepancies, ultimately determining the final set of literature included in the analysis.

In terms of analytical methodology, this study employs a combination of thematic synthesis and critical review. First, based on findings from the included literature, a core logical chain was extracted and constructed: "Digital Rural Development → Socioeconomic Effects → Farmer Behavioral Responses → Energy Structure Transformation". Second, literature was systematically organized and comparatively analyzed across three dimensions—theoretical mechanisms, empirical evidence, and policy interventions—with a focus on examining the intrinsic mechanisms through which digital technologies influence farmers' energy decisions via multiple pathways, including income growth, information empowerment, infrastructure coordination, social network diffusion, and capacity building. Simultaneously, this paper critically examines existing research limitations and divergences in identifying micro-level mechanisms, assessing long-term effects, and analyzing policy synergies. Through critical synthesis, it not only systematically maps the knowledge landscape of this field but also provides clear directional guidance for future research.

Through this systematic, transparent, and reproducible literature review, this study aims to provide a robust and comprehensive knowledge foundation for understanding the complex relationship between digital rural development and farmers' green energy consumption. It ensures that all perspectives and conclusions presented are grounded in rigorous empirical evidence.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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