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Does digital finance affect energy consumption structure upgrading? Evidence from Chinese rural households

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ABSTRACT

As carbon neutrality debates escalate, household energy use has gained prominence of scholars. However, existing studies overly focus on consumption expenditure while sidelining the impact of digital finance. This research utilized Chinese household microdata to explore the nexus between digital finance and household energy structure. The empirical results confirm its facilitative effect. The mechanisms of action include infrastructure construction, increased household environmental literacy, improved payment environments, and enhanced risk hedging ability. Regional and policy heterogeneities exist, and the energy structure upgrading aligns with the energy stacking theory. The findings thus shed light on digital finance's role in promoting sustainable household energy transitions.

1. Introduction

As carbon neutrality attracts growing attention, energy consumption has become one of the most pressing and widely discussed topics by researchers. According to the International Energy Agency's (IEA) Global Energy Review 2025, global carbon dioxide emissions related to energy use reached 37.8 billion tons in 2024, an increase of 0.8 % year on year, setting a new record high. In the past, greater attention was focused on production-related carbon emissions. However, the reality is that households are responsible for a greater proportion of total carbon emissions: according to the United Nations, over 70 % of worldwide carbon emissions result from household energy use. The increasingly high levels of carbon emissions are a constant reminder of the importance of attending to energy consumption, focusing not only on its quantity but also on the intricacies of its structural composition. Accordingly, optimizing and upgrading the structure of household energy consumption is of great practical significance.

At the same time, digital finance has continued to evolve, changing the scenarios and modes of traditional finance, with particular benefits for individuals excluded by traditional services. In today's rapidly evolving financial landscape, digital finance has emerged as an informational force reshaping financial transactions and services through innovations such as electronic payment systems, online banking, and mobile wallets (Singh & Rana, 2017). Beyond its immediate financial implications, digital finance impacts various dimensions of society and the economy, which may include energy consumption (Cao et al., 2021; Dong et al., 2021; Qin et al., 2022).

The rapid growth of digital finance and rising concerns about energy consumption raise the following questions: Does digital finance impact the structure of household energy consumption? If so, what mechanisms drive this impact? Is its impact heterogeneous?

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In addition, which of the energy ladder or energy stacking theory is more suitable for explaining the upgrading of the structure of household energy consumption? According to Van der Kroon et al. (2013), the energy ladder theory suggests that upgrading energy consumption is a form of linear laddering (see Fig. 1): rural households will not use lower-level energy once it reaches a higher level. By contrast, the energy stacking theory suggests that families will use multiple forms of energy simultaneously during the upgrading process. We explore which theory better describes household energy upgrading.

Our empirical study is motivated by the following observations. First, energy use by rural households in China is steadily increasing, but the structure of this consumption and its implications for residents' welfare and for the environment are raising concerns (Han & Wu, 2018). In particular, poorer households in rural areas are often forced to allocate substantial time toward obtaining and processing lower-quality energy resources, which depletes labor hours and restricts educational opportunities (Morris et al., 2010). Second, the use of inefficient energy sources like biomass may contribute to environmental and climate-related issues, notably indoor air pollution (Dutta et al., 2007). Third, the burgeoning of digital finance in China offers rural households potential avenues for altering their patterns of energy consumption (Pu & Fei, 2022). In recent decades, the Chinese government has made significant investments in digital infrastructure, especially with its "rural revitalization strategy."

The present paper has both academic and policy significance. First, the objective of the study is to elucidate the organic connections that exist between financial development, energy use, and rural economy. This will offer a conceptual foundation for a deeper understanding of rural finance and energy, facilitating equitable growth in rural economies and enhancing energy efficiency. Second, this investigation adds to the body of knowledge in digital finance, energy economics, and household research. By examining the influence of digital finance on the energy usage patterns of rural households, it sheds light on the important role of digital finance in fostering rural economic progress and energy shifts while also offering novel insights and theoretical constructs. Third, the findings of this paper may inform the formulation of more precise and effective rural energy policies. Understanding how digital finance works can help policymakers better grasp the needs and trends of the rural energy market and, thus, design more targeted policy measures. It can also help raise the energy consumption awareness and capacity of rural households and improve their life quality and sustainable development.

We propose several hypotheses derived from theoretical analysis. Employing data collected by the Chinese Resident Energy Consumption Survey (CRECS), the Chinese General Social Survey (CGSS), and the Digital Financial Inclusion Index (DFII), we designed empirical models to study the nexus between digital finance and energy structure. The generalized method of moments (GMM) and instrumental variable method were used to detect potential endogeneity issues. We verified several effect mechanisms, including infrastructure construction, increased household environmental literacy, improved payment environments, and enhanced risk hedging ability. In addition, we analyzed regional and governmental policy heterogeneity. Finally, we explored whether the upgrading process can be explained by the energy stacking theory.

Our study makes the following novel contributions. First, in contrast to the general practice of employing macro data, we use household-survey microdata, thereby shedding new light on the nexus between digital finance and household energy upgrading. Second, we investigate the mechanisms underlying the identified impact to offer reasonable explanations. Third, we incorporate energy stacking theory and show that it provides unique insights for policymakers wishing to craft precise policy instruments in the future.

The remainder of the article is structured as follows. In Section 2, we review the literature. In Section 3, we articulate our research hypotheses. We lay out our empirical strategy in Section 4 and detail our empirical results in Section 5. Lastly, Section 6 offers a

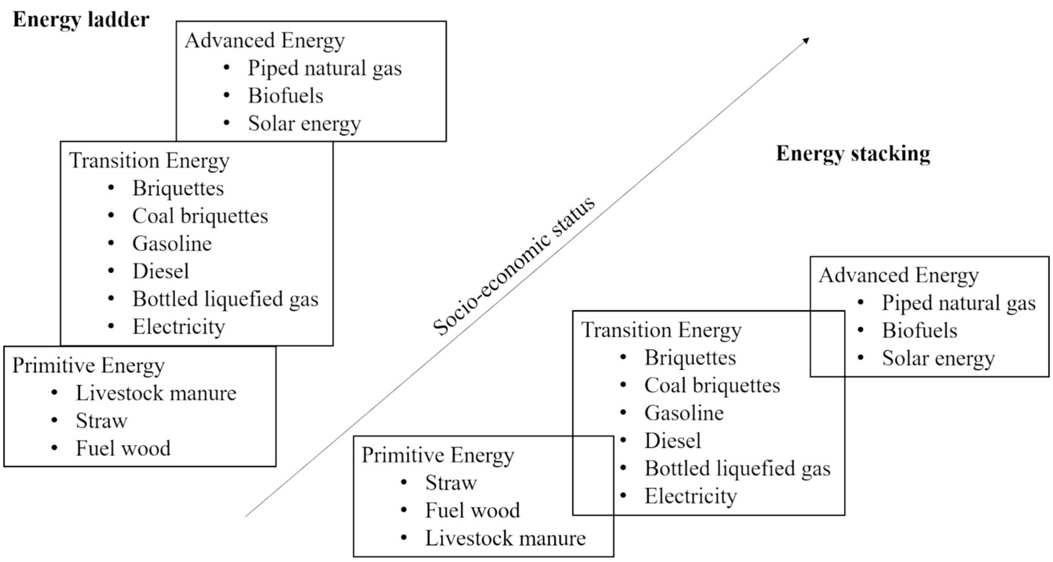

Fig. 1. The processes of energy source transition.
Reference to Van der Kroon et al. (2013).

conclusion.

2. Literature review

2.1. Digital finance and energy

Digital finance refers to the transformative changes in the financial sector brought about by the introduction of information and communication technology (Gomber et al., 2017). Scholars have pointed out that the development of digital finance impacts household risk-taking, economics, carbon footprints, technology, inequality, and the environment (Burlacu et al., 2021; Cao et al., 2021; Hu et al., 2024; Wang et al., 2025). In particular, numerous studies have discussed the effect of digital finance on household consumption. Li et al. (2020) confirmed that it effectively stimulates individual consumption, mostly by amplifying regular rather than irregular expenditure. Hu et al. (2023) also observed that the evolution of digital finance contributes to the upgrading of family consumption, which is associated with the easing of liquidity constraints, an improved payment environment, and investment efficiency.

Regarding energy use, from a social and industrial perspective, the digital economy promises to alleviate energy poverty and foster low-carbon development. Notably, advancements in internet-related technologies can reduce traditional energy dependency in various industries, facilitating industrial upgrades and optimizing energy efficiency. In this regard, Dong et al. (2021) highlighted the effective role of the digital economy in driving supply- and demand-side energy transition. Cao et al. (2021) similarly identified a substantial enhancement in China's energy-environmental performance attributable to digital finance through green technology innovation. Green innovation and renewable energy business are also prompted by the digital economy (Li et al., 2025; Zheng et al., 2025).

At the micro level, scholars have focused on carbon emissions. Given the significant impact of digital finance on household consumption, energy consumption—a subset thereof—is also bound to be impacted. Research on the mechanism of action reveals a dual relationship, with digital finance stimulating the scale of consumption and increasing emissions while simultaneously promoting greener consumption patterns that lead to reduced emissions. The scale effect outweighs the composition effect (Qin et al., 2022). Some scholars have identified an inverted U-shaped relationship between digital finance and renewable energy business, corroborating the environmental Kuznets curve theory (Li & Wang, 2022), while some researchers observed a linear effect (Huang et al., 2024). Luan et al. (2023) proposed that the digital divide disproportionately affects energy poverty alleviation among lower-income, elderly, and rural households. A non-linear correlation between digital finance and carbon performance is also verified (Zhou et al., 2024).

2.2. Energy structure upgrading

Scholars have proposed two main paths of energy structure upgrading: the energy ladder and energy stacking. The former compares energy upgrading to climbing a ladder, painting it as a linear, mutually exclusive transition between different sources of energy. The latter emphasizes that during upgrading, different energy sources can coexist in a non-linear and gradual process.

2.2.1. Energy ladder

Studies have suggested that household energy consumption represents an energy ladder phenomenon (Hosier & Dowd, 1987). This phenomenon is often used to explain the structural upgrading of energy consumption, with the upgrading of a household's energy mix being argued to be analogous to the linear progression of climbing a staircase. The energy ladder theory, illustrated in Fig. 1, proposes that with social and economic progress, households tend to shift from traditional, dirty, and inefficient energy sources like biomass and animal waste to cleaner and more efficient ones such as electricity and natural gas (Choumert-Nkolo, Motel, & Le Roux, 2019). Scholars have empirically tested this hypothesis using diverse regional data. Meried (2021), for example, used a dataset of rural households in North Gondar to verify the energy ladder theory. Similarly, Fentie et al. (2023) found evidence of an energy ladder using data on lighting fuels in Ethiopia. Jia et al. (2022) used a machine learning approach to demonstrate the ladder phenomenon in the context of carbon neutralization.

Nonetheless, some scholars argue that there may be regional deviations from this upgrading model, where the transition from biomass to "modern" fuels does not necessarily mean that wood fuels are replaced as the dominant energy source. This apparent regional deviation may be attributable to a lack of attention in household energy-switching models to the significant role played by urban consumers' proactive and strategic decision-making and responses to relative fuel prices (Hiemstra-Van der Horst & Hovorka, 2008).

2.2.2. Energy stacking

Other researchers have proposed the energy stacking theory to challenge the notion of a straightforward replacement of primitive energy sources with higher-quality sources during energy transitions. Energy stacking posits that household energy upgrading is not a linear process of ladder climbing and can instead be understood as nonlinear stacking. In contrast to the earlier theory, energy stacking emphasizes the period of transition in the process of energy upgrading. In other words, energy upgrading does not mean instantaneously abandoning traditional energy; there is a phase when a mix of traditional and advanced energy is used while moving toward advanced energy sources.

For instance, Masera et al. (2000) observed the energy stacking phenomenon in rural Mexico, where multiple fuel sources coexist, offering a more accurate depiction of fuel choices for cooking purposes. Alem et al. (2016) came to a similar conclusion, suggesting that income promotes energy transitions but not linearly as in an energy ladder, resembling an energy stack instead. Choumert-Nkolo et al. (2019) used a Tanzanian dataset to discuss the phenomenon of rural households' energy consumption stacking and found that where various fuels are available, households with higher incomes tend to use modern fuels, especially for electricity. Taking India as an example, Yadav et al. (2021) pointed out that multi-fuel use is prevalent in the early and middle stacking stages of household energy consumption. That is, households do not abandon traditional sources of energy. Therefore, fuel stacking may remain a crucial aspect of socio-cultural energy traditions and influence the transition to low-carbon and clean energy. This results in inherent policy complexities and contradictory theories of the energy transition, revealing a policy dilemma.

2.3. Research gaps

The existing studies mostly focus on energy consumption quantity and efficiency, primarily at the macroeconomic level. However, limited attention is paid to household energy upgrading, particularly the role of digital finance. Moreover, while the energy stacking theory more closely reflects reality, the upgrading model has rarely been empirically tested. With the present study, we bridge these gaps using data from Chinese households and illuminate the relatively unexplored dimension of the digital finance–energy consumption nexus to verify the validity of the upgrading model.

3. Research design and hypotheses

3.1. Baseline effects

3.1.1. Quantitative analysis

The energy used by households can be divided into three categories: primary energy, transitional energy, and advanced energy. In the quantitative analysis, transitional energy can be classified as primary energy. Therefore, to simplify the analysis, we divided household energy use into two categories in our analytical framework: primary energy use (e.g., firewood and coal) and advanced energy use (e.g., natural gas and solar energy). Some basic energy sources, such as firewood and animal dung, can be procured self-sufficiently by households, without the need to purchase them on the market. Conversely, advanced energy sources can only be obtained through purchase. We define the upgrade of the energy consumption structure as an increase in the proportion of advanced energy use in total energy use.

Assuming a large number of homogeneous and infinitely persistent households in the economy, the utility function of a representative household is time-separable, and its instantaneous utility function is as follows:

$$u\left(C_t^1, C_t^2\right) = \ln C_t^1 + \ln\left[\tau(1-N_t) + C_t^2\right]. \tag{1}$$

where C_t^1 represents the basic energy consumption of households through purchases in period t, C_t^2 represents the advanced energy consumption of households in period t, N_t represents the working hours of households, and $1-N_t$ represents the standardized leisure time of households. τ is the efficiency coefficient of household basic energy, that is, the amount of energy consumed by households in a self-sufficient manner per unit of time. This coefficient is negatively correlated with the level of digital financial development, meaning that digital financial development will prompt households to shift to more efficient, market-based methods of energy acquisition and consumption. For instance, from the perspective of opportunity cost, digital finance increases the accessibility of market-based high-grade energy (e.g., electricity and natural gas), and households are more inclined to use their free time for other high-value-added activities (e.g., online education and side businesses) than for self-sufficient energy production.

The objective function of social planners is set as:

$$\max_{\left\{C_t^1, C_t^2, N_t\right\}_{t=0}^{\infty}} E_t\left(\sum_{t=0}^{\infty}\beta^t\left(\ln C_t^1 + \ln\left[\tau(1-N_t) + C_t^2\right]\right)\right), \tag{2}$$

$$s.t. C_t^1 + C_t^2 + K_t = Y_t + (1-\delta)K_{t-1}, \tag{3}$$

$$C_t^1 \geq 0, C_t^2 \geq 0, 0 \leq N_t \leq 1, K_0 \geq 0.$$

The production function and technological shock are determined by the following formula:

$$Y_t = (A_t N_t)^{1-\alpha} K_{t-1}^{\alpha} \tag{4}$$

$$\log A_t = \rho \log A_{t-1} + u_t \text{ and } u_t \sim N(0, \sigma_u) \tag{5}$$

Technological progress A_t reflects the improvement in total factor productivity brought about by the development of digital finance. In the energy sector, this can be more specifically defined as the efficiency of clean energy technology. For example, digital finance platforms (e.g., green bonds and crowdfunding) lower the financing threshold for clean technologies (e.g., photovoltaic power generation and energy storage systems), accelerate technological research and development and applications, and directly enhance A_t. This has a positive effect on the equilibrium output level Y_t. A higher output increases household income, enabling households to afford the cost of using more market-based advanced energy sources.

By solving the first-order condition, we obtain:

$$\frac{-\tau}{\tau(1-N_t)+C_t^2}+\frac{\beta^t}{C_t^1}(1-\alpha)\frac{Y_t}{N_t}=0, \tag{6}$$

$$\beta E_t\frac{1}{C_{t-1}^1}\left[\alpha\frac{Y_{t+1}}{K_t}+1-\delta\right]=\frac{1}{C_t^1}, \tag{7}$$

$$\beta E_t\frac{1}{\tau(1-N_{t+1})+C_{t+1}^2}\left[\alpha\frac{Y_{t+1}}{K_t}+1-\delta\right]=\frac{1}{\tau(1-N_t)+C_t^2}, \tag{8}$$

$$\frac{C_t^1}{\tau(1-N_t)+C_t^2}=1. \tag{9}$$

The steady state of the economy has the following result:

$$\frac{C_t^2}{C_t^1+C_t^2}=\frac{1}{2}\left[1-\frac{\frac{\tau}{Y}-\beta^t(1-\alpha)}{1-\frac{\delta\alpha}{\frac{1}{\beta}-(1-\delta)}}\right]. \tag{10}$$

The proof is provided in Appendix A. According to Eq. (10), digital finance promotes household energy consumption upgrading.

3.1.2. Theoretical analysis

Digital finance, which relies on internet platforms and digital technology, is expected to stimulate the usage of higher-quality energy sources. To access diverse digital finance services, households need modern digital devices, which boosts their demand for advanced energy (Ruta et al., 2017). Digital finance offers strong financial support for household energy consumption upgrades. The booming development of digital payment and financial technology has dramatically changed household consumption patterns. In the past, the purchase of clean energy equipment, such as solar water heaters and wind turbines, or the adoption of renewable energy sources, could be hindered by financial concerns as well as complicated payment processes. In contrast, digital financial instruments now allow households to quickly complete the purchase of clean energy equipment or easily connect to the renewable energy supply network through convenient online payment methods. In addition, the emergence of green financial products has provided strong financial incentives for households to choose high-grade energy. For example, green loans offered by financial institutions provide financial support for and significantly reduce the cost of purchasing clean energy equipment through measures such as preferential interest rates. Such economic benefits incentivize more households to try and embrace higher-grade energy. Finally, digital financial technologies provide personalized energy solutions. Through data analytics and artificial intelligence, the system can provide personalized energy-saving advice based on a household's energy usage patterns. This personalized service stimulates households' interest in clean energy because they can manage their energy more efficiently and lower their energy bills while contributing to environmental protection. Some of the indirect effects of digital finance can also lead households to increase their consumption of high-quality energy. For example, the digital economy often emphasizes environmental protection, efficiency, and sustainability. Therefore, households with higher levels of digital finance usage tend to be more receptive to these concepts and focus on high-quality choices when it comes to energy consumption. The advancement of digital finance thus incentivizes households to augment their consumption of top-tier energy sources. This phenomenon reflects an upgrade to the structure of household energy consumption, namely, a gradual shift toward higher-tier energy sources. Accordingly, we propose the following hypothesis:

H1. Digital finance leads to the upgrading of the structure of household energy consumption.

3.2. Mechanism analysis

3.2.1. Infrastructure development

Digital finance fundamentally relies on robust digital infrastructure, which serves as a critical channel for reshaping household energy choices. The proliferation of digital financial services necessitates widespread access to high-speed internet and smart devices, which concurrently drives investments in complementary energy infrastructure such as smart grids and renewable energy distribution networks. In rural China, the government's Digital Village initiative is intended to accelerate broadband penetration and mobile payment coverage. This infrastructure synergy reduces the transaction costs of adopting advanced energy sources (e.g., solar panels, biogas systems) by enabling seamless online financing, remote monitoring, and real-time payment solutions.

For instance, households in remote areas previously constrained by limited banking access can now leverage mobile banking to finance rooftop solar installations through microloans. Digital platforms further integrate energy suppliers and consumers, facilitating peer-to-peer energy trading and dynamic pricing models (e.g., time-of-use tariffs), which incentivize shifts toward electricity and renewables. In addition, regions with higher digital infrastructure density exhibit faster adoption of clean energy technologies because reduced information asymmetry and enhanced financing options lower barriers to entry. Consequently, digital infrastructure acts not merely as a facilitator but as a catalyst for energy transition by embedding advanced energy into daily consumption patterns. Accordingly, we propose the following hypothesis:

H2. Digital finance promotes household energy consumption upgrading by accelerating infrastructure development.

3.2.2. Improvements in environmental awareness

Digital finance platforms are crucial vectors for disseminating environmental information and shaping pro-environmental behaviors. By integrating sustainability metrics into financial products (e.g., carbon footprint trackers, green credit scores), these platforms boost households' awareness of the environmental externalities associated with traditional energy use. Behavioral nudges such as real-time feedback on energy-related emissions via e-wallets or discounts for renewable energy purchases strengthen the link between consumption choices and ecological impact.

For instance, Ant Forest is a public welfare project launched by Alipay in 2016, which accumulates green energy through users' low-carbon paying behaviors to support reforestation and ecological protection. Ant Forest's model, where users earn carbon credits for low-carbon transactions, demonstrates how financial interactions can help them internalize environmental values. Users accumulating credits for virtual trees trigger real afforestation projects, reinforcing the perception that individual energy choices contribute to collective environmental goals. Furthermore, algorithm-driven recommendations on digital purchasing platforms amplify exposure to green energy products.

This awareness-to-action pathway is more likely to be potent in rural contexts, where traditional energy practices are deeply entrenched. Digital finance transcends transactional functions to cultivate a cognitive foundation for sustainable energy transitions. Thus, the following hypothesis is proposed:

H3. Digital finance enhances environmental awareness, thereby facilitating household energy consumption upgrading.

3.2.3. Payment environment improvement

Digital finance can reduce the time cost and the shoe-leather cost of transactions, enhancing the convenience of transactions. Consequently, digital finance is conducive to increasing the frequency and volume of transactions. For household energy consumption, the path of access to primitive energy and transition energy is relatively fixed and not easily affected by digital finance, while the consumption of higher-quality energy, such as electricity and bioenergy, can ride on the tailwinds of digital means, making it easier and more favorable for households to access higher-quality energy. For example, for online payment, people only need to use cell phones or computers and other terminal equipment to instantly complete transfers of funds or receive transaction confirmations, greatly reducing the time cost of transactions. At the same time, digital finance limits cumbersome offline procedures and intermediate links, such as the transmission of paper documents and manual review processes, which are no longer necessary steps in the transaction. This significantly lowers transaction costs. In addition, increased payment convenience highlights another significant drawback of traditional energy sources: the cost of storage. As digital finance improves the payment environment and makes payment easier, households also tend to be mindful of the storage costs associated with their purchases. Higher-quality energy sources like electricity and bioenergy have essentially no storage costs, whereas lower-quality energy sources such as coal and fuel wood crowd out a household's storage space and impose storage costs. Higher-quality energy is thus preferred by households.

For instance, in China's mountainous regions, households traditionally procured coal in bulk, a practice entailing upfront storage costs. The 2014 launch of State Grid's "e-Power" service on WeChat introduced two effective platforms: prepaid electricity with dynamic pricing (offering off-peak rates 60 % below standard prices) and automatic balance replenishment (mitigating outage risks through low-balance triggers). This digital convenience incentivizes households to transition from coal-based heating to electric alternatives, directly reducing the implicit storage costs associated with primary energy consumption. Concurrently, transparent pricing accelerates substitution by advanced energy sources as a whole.

Thus, we propose the following hypothesis:

H4. Digital finance can contribute to upgrading household energy consumption by improving payment convenience.

3.2.4. Risk-hedging ability enhancement

Importantly, although advanced energy is more expensive than primitive and transition energy sources, it can bring more utility to households in a digital environment. In other words, if households choose higher-quality energy as their primitive energy source for consumption, this can increase stress related to financial risk. However, digital finance, as a unique financial instrument, is universally resilient to risk and can make households more resilient by providing quicker, more convenient, and diverse insurance services.

Digital financial instruments offer additional mechanisms for risk management and insurance to reduce households' uncertainty when upgrading their energy consumption. For example, insurance products available in the financial market can cover damage or failure of renewable energy equipment, reduce the risks households face when using the equipment and increase their confidence. Digital financial platforms also enhance the sustainability and transparency of household energy consumption by offering risk management tools and information services. Households can utilize the tools and services on digital financial platforms to assess their energy consumption, manage risks, and adjust to market changes.

These risk management and information services help households approach their energy consumption in a more scientific and rational way, promoting a shift in the structure of energy consumption toward sustainable development. For example, many rural households were previously reluctant to adopt solar panels due to installation and maintenance cost barriers. In 2023, Ping An Bank addressed this through its green finance initiative, providing low/zero-threshold loans, which enable customers to acquire premium distributed photovoltaic systems within 7 days and integrate a digital profit model generating supplemental green revenues while utilizing clean energy. With increased risk resistance, households have greater confidence in consuming higher-quality energy and upgrading their energy structure. Ultimately, this strengthens households' ability to cope with uncertainty, releasing household purchasing power for the use of more advanced energy sources and cleaner equipment. In light of this, we propose Hypothesis 5:

H5. Digital finance can increase household resilience and, thus, contribute to upgrading household energy consumption.

3.3. *Pattern of energy upgrading*

Households bear the financial burden of acquiring the digital devices and services necessary for accessing digital finance. Furthermore, digital finance entails energy-related expenditures. When the costs linked to these higher-quality energy sources are prohibitively high, households may opt for cost-effective secondary energy sources, resulting in an energy stacking phenomenon. Additionally, digital finance can help households diversify their energy consumption portfolio, potentially expanding their energy sources. In the long run, as digital finance reaches a certain level of maturity, the benefits are likely to surpass the associated costs. Moreover, digital finance tends to rely more heavily on high-tier energy sources. At this juncture, households may exhibit a preference for fewer energy categories and a growing inclination toward higher-tier energy sources. This transition ultimately may lead to a reduction in the diversity of energy sources consumed. This pattern amounts to a gradual transition from lower-tier to higher-tier energy sources in the household energy consumption structure. Accordingly, we formulate the following hypothesis:

H6. Energy structure upgrading follows the theory of energy stacking.

4. Data

4.1. *Data description*

Our study focuses on rural households because, although China has made great strides in urbanization, rural areas still account for up to 95 % of the land area and 36 % of the population. Rural households consume more types of energy and still exhibit diverse energy consumption structures. A rural household may use firewood, coal, and electricity simultaneously.

We sourced energy-related data from the CRECS and CGSS, both of which are conducted by Renmin University of China. We sampled rural households from the 2013 and 2014 CRECS datasets and the 2015 and 2018 CGSS datasets.[1] Following Wu et al. (2019), our study combined the data from these years into a pooled sample for analysis. The data on digital finance were taken from the DFII, jointly released by Ant Financial Services Group and Peking University. We combined data from different databases and matched them based on the county in which the household is located. After applying a 1 % winsorization, a total of 9252 observations remained.

4.2. *Variables*

4.2.1. *Core variables*

We used whether households are higher-quality energy users (*ES*) as the core dependent variable; *ES* served as a proxy for household energy consumption upgrading. According to the CRECS and CGSS, households may potentially consume 12 different types of energy. Following previous studies (Van der Kroon et al., 2013; Wu et al., 2019), we categorized the 12 energy types into three: primitive energy, transition energy, and advanced energy.[2] The *ES* variable takes the value of 1 if the household's advanced energy consumption expenditure is greater than 50 % and 0 otherwise.

We employed *DFII* as the core independent variable to gauge digital financial development. This multifaceted metric captures regional digital financial growth across services, the intensity of their utilization, and the level of digitalization in financial inclusion.

4.2.2. *Control variables*

Building on relevant studies, we chose four types of control variables. First, we selected indicators relating to family demographic characteristics, including family income, family size, household head education, age, and gender (Dong et al., 2021). We also introduced variables characterizing the head of the household because of the long-standing influence of Confucianism in China, where the household head is often the family breadwinner and the day-to-day decision-maker for the household. Second, households' energy needs are impacted by their home's construction (Alem et al., 2016), so we included in our analysis the structure of the windows and

[1] The CRECS surveys were conducted in 2012–2017, 2021, and 2022. The base year for the survey was 2012. The 2013–2014 surveys focused on household energy consumption in China. Starting in 2015, these questions were incorporated into the CGSS survey, and the CRECS shifted its focus to coal governance, carbon awareness, and cooling. Only the 2015 and 2018 questionnaires for the CGSS included energy-related questions. The CGSS and CRECS maintained good consistency in the sampled households, and even though the CRECS survey was integrated into the CGSS survey, this did not affect its traceability and representativeness. Therefore, due to data availability constraints, we selected data from 2013, 2014, 2015, and 2018 for our empirical analysis.

[2] Primitive energy includes livestock manure, straw, and fuel wood. Transition energy includes briquettes, coal briquettes, gasoline, diesel, and electricity. Advanced energy includes bottled liquefied gas, piped natural gas, biofuels, and solar energy.

doors, the type of glazing, the presence or absence of warming measures, and the presence or absence of insulation. Third, the regional climate and the number of hours of sunlight per day in the household's location determine the temperature (Wu et al., 2019), the most critical climatic factor. We thus chose the average daily sunshine hours in summer and winter as the control variables. Finally, the influences of the regional macroeconomic environment, regional GDP, and regional fiscal expenditure were added as control variables. The definitions of all indicators are presented in Table 1.

Table 2 summarizes the descriptive statistics of the variables.

4.3. Model

4.3.1. Baseline regression model

We employed the following logit regression to evaluate the impact of digital finance:

$$\mathrm{Logit}\ (\mathrm{ES}_{ict} = 1) = b_0 + b_1\ \mathrm{DFII}_{ct} + X'_{ict}\ \beta + \eta_i + \delta_c + \theta_t + \varepsilon_{ict} \tag{11}$$

where ES_{ict} captures whether household i in city c and year t is a higher-quality energy household, b_0 is the intercept, b_1 measures the impact of digital financial development, X'_{ict} denotes all the control variables, and their effects are measured by β. η, δ, and θ represent the household, city, and year fixed effects, respectively. ε_{ict} is the error term.

4.3.2. Mechanism examination model

To verify the three influencing mechanisms proposed in Section 3.2, we selected proper mediating variables and used the following model:

$$\mathrm{M}_{ict} = c_0 + c_1\ \mathrm{DFII}_{ct} + X'_{ict}\ \beta + \eta_i + \delta_c + \theta_t + \varepsilon_{ict} \tag{12}$$

$$\mathrm{Logit}\ (\mathrm{ES}_{ict} = 1) = a_0 + a_1\ \mathrm{DFII}_{ct} + a_2\ \mathrm{M}_{ict} + X'_{ict}\ \beta + \eta_i + \delta_c + \theta_t + \varepsilon_{ict} \tag{13}$$

where M_{ict} denotes the mediating variables, and other terms are the same as in Eq. (11).

5. Empirical research

5.1. Baseline study

Table 3 reports the results of the baseline effect. The coefficients show a significant promotion effect of *DFII* on *ES*, indicating that digital finance can promote the acquisition of higher-quality energy by households and the upgrading of energy structure. Therefore, our empirical results support **H1**, suggesting that digital finance matters in households' choice to use advanced energy sources.

As concerns the control variables, several findings emerged. First, we observed a clear positive effect of a household's income (*Income*), a result that is consistent with economic theory and common sense. Choosing a higher grade of energy means a higher energy bill, which requires a sufficient household income. Second, more educated households (*Edu*) were more motivated to use high-quality energy as their main source of energy consumption. This is likely because household heads who are more educated are likely to grasp the importance of new energy technologies and embrace them, and they are eager to switch to cleaner energy options to reduce their environmental impact. In addition, households with higher educational attainment are usually more financially affluent, and they are more capable of purchasing and using expensive, high-quality energy or clean energy devices, such as solar panels and ground-source heat pumps. Third, the coefficient of household size (*Household_Size*) is statistically significantly positive, implying that the larger households in our sample tended to favor advanced energy. This may be due to the fact that advanced energy usually has higher energy efficiency. Gas ovens or stoves burn much more efficiently than traditional wood-burning cookers, providing heat faster to meet the cooking and heating needs of families. This high efficiency is especially important in larger households, given that it reduces energy consumption and saves time and costs. At the same time, advanced energy is more convenient and comfortable to use. Compared to wood stoves, which require the constant addition of firewood, gas stoves control the heat by simply adjusting the size of the flame, making them easy to operate, clean, and hygienic. In addition, the gas supply is stable and not affected by the weather, making it suitable for continuous use by large families. Fourth, we noted a tendency for households in areas with long summer sunshine hours (*Sum_Sunshine*) to prefer more advanced energy. A possible explanation is that during the summer months, daytime temperatures are higher and households need to use air conditioners or fans, which cannot rely on traditional sources of energy, such as fuelwood, to operate. Lastly, a higher regional gross domestic product (*GDP*) and fiscal expenditures (*Fiscal*) indicate that people in the region can afford higher-priced energy, and these regions frequently lead the energy transition and the implementation of clean energy policies. The results align with the theory of energy upgrading, suggesting that as households' economic status and social standing improve, they tend to develop better energy consumption patterns.

Because ES measured the upgrading of household energy consumption in relative terms, we used the absolute value to run the regression to further investigate the effect. That is, we took the three energy types (primary, transitional, and advanced energy[3]) as a core dependent variable. The goal was to show the effect of digital financial development from the perspective of absolute

[3] The definition is provided in footnote 3.

Table 1
Indicators.

Type	Symbol	Definition
Core dependent variable	*ES*	1 if the household's advanced energy consumption expenditure is greater than 50 % of total energy consumption expenditure and 0 otherwise
Core independent variable	*DFII*	Digital financial inclusion index
Control variables	*Income*	Household income
	Size	Family size
	Gender	1 for male, 0 for female
	Age	Household head's age
	Edu	Household head's education level[1]
	Win_Door	Structure of the windows and doors[2]
	Glazing	Type of glazing[3]
	House_size	Housing area
	Warming	1 for having warming measures, 0 otherwise
	Insulation	1 for having insulation measures, 0 otherwise
	Win_Sunshine	Winter sunshine hours per day
	Sum_Sunshine	Summer sunshine hours per day
	GDP	$Ln(Regional\ GDP)$
	Fiscal	$Ln(Regional\ Fiscal\ expenditure)$
Instrument variables	*IV* 1	The number of post offices per million people in each city in 1984 multiplied by the national internet investment of the previous year
	IV 2	Spherical distance from home city to Hangzhou (Unit: 1000 km)
Mediating variables	*Infra*	The length of the natural gas pipeline divided by the permanent resident population (in millions) in the area of the home
	Literacy	The extent to which households agree that individuals have a very limited role to play in controlling energy consumption and improving the environment
	Payment	*E*-commerce sales divided by regional per capita consumption expenditure in the region
	Insurance	The regional internet insurance premium income divided by regional per capita consumption expenditure
Other variables	*ESTA*	$ESTA = 1$ if the household used only primary energy, $ESTA = 2$ if the household used a mix of primary and transition energy, $ESTA = 3$ if the household used only transition energy, $ESTA = 4$ if the household used a mix of transition and advanced energy, and $ESTA = 5$ if the household used only advanced energy.
	ET	The number of energy types consumed by the household

[1] No education: 0; elementary school education: 1; middle school education: 2; high school education: 3; undergraduate education: 4; graduate education: 5.
[2] Wood: 1; iron: 2; plastic: 3; aluminum alloy: 4.
[3] Single glazing: 1; double glazing: 2; triple glazing: 3.

Table 2
Descriptive statistics.

Type	Symbol	N	Mean	Median	Max	Min	Std
Core dependent variable	*ES*	9252	0.574	0	1	0	0.239
Core independent variable	*DFII*	9252	21	211.28	377.73	118.01	31.29
Control variables	*Income*	9252	8.657	6.346	10.270	0	1.377
	Size	9252	3.923	3	15	1	1.792
	Gender	9252	0.538	1	1	0	0.496
	Age	9252	46.824	48.259	99	18	11.655
	Edu	9252	2.105	2.363	5	0	0.379
	Win_Door	9252	2.568	2.035	4	1	0.734
	Glazing	9252	2.129	2	3	1	0.418
	House_size	9252	98.815	93.275	280	7	65.327
	Warming	9252	0.573	1	1	0	0.256
	Insulation	9252	0.471	1	1	0	0.239
	Win_Sunshine	9252	3.105	3.862	9	0.5	2.853
	Sum_Sunshine	9252	9.467	7.328	16	3	2.404
	GDP	9252	9.126	8.317	11.485	7.651	2.106
	Fiscal	9252	8.155	7.364	9.664	7.132	1.853
Instrument variables	*IV* 1	9252	4.873	3.927	10.903	2.371	1.059
	IV 2	9252	1.295	1.120	4.078	0	0.819
Mediating variables	*Infra*	9252	0.047	0.031	0.129	0.017	0.061
	Payment	9252	0.371	0.359	0.663	0.243	0.095
	Insurance	9252	0.294	0.314	0.661	0.176	0.052
	Literacy	9252	2.784	3	5	1	0.447
Other variables	*ESTA*	9252	2.476	2	5	1	0.963
	ET	9252	4.015	3	9	1	1.364

Table 3
Baseline results.

Variables	*ES*	*ES*	Primary	Transitional	Advanced
	(1)	(2)	(3)	(4)	(5)
DFII	0.039***	0.035***	−0.009	0.023***	0.020***
	(0.005)	(0.006)	(0.007)	(0.008)	(0.008)
Income		0.0133***	−0.0057***	0.0086***	0.0097***
		(0.004)	(0.002)	(0.003)	(0.004)
Size		0.047	0.058	0.0028	0.0022
		(0.032)	(0.0039)	(0.0049)	(0.0054)
Gender		0.0840	0.0375	0.0532	0.0429
		(0.0821)	(0.0961)	(0.0814)	(0.0790)
Age		−0.005	0.007	−0.002	−0.004
		(0.004)	(0.005)	(0.004)	(0.006)
Edu		0.461***	−0.098**	0.087*	0.284***
		(0.044)	(0.052)	(0.049)	(0.063)
House_size		0.003**	0.002*	0.002**	0.003***
		(0.0008)	(0.0012)	(0.0009)	(0.0010)
Win_Door		0.264***	0.108***	0.157***	0.136***
		(0.025)	(0.033)	(0.041)	(0.044)
Glazing		0.116	−0.082	0.158	0.101
		(0.097)	(0.089)	(0.092)	(0.084)
Warming		−0.0683***	−0.0384**	−0.0469***	−0.0401**
		(0.0214)	(0.0198)	(0.0233)	(0.0218)
Insulation		0.376**	0.417***	0.393***	0.362**
		(0.195)	(0.202)	(0.172)	(0.186)
Sum_Sunshine		0.0782***	0.0697***	0.0604**	0.0737***
		(0.0380)	(0.0335)	(0.0316)	(0.0359)
Win_Sunshine		−0.119***	−0.066***	−0.105***	−0.128***
		(0.034)	(0.034)	(0.046)	(0.047)
GDP		0.0014**	−0.0022***	0.0047***	0.0037***
		(0.0007)	(0.0010)	(0.0021)	(0.0015)
Fiscal		0.0003***	−0.0013***	0.0009***	0.0005***
		(0.00005)	(0.0001)	(0.00009)	(0.0001)
Constant		−8.569***	5.433***	6.227***	−3.012***
		(0.893)	(1.931)	(2.015)	(0.752)
Fixed effects	Yes	Yes	Yes	Yes	Yes
Adj-R^2	0.464	0.541	0.317	0.398	0.403
Observations	9252	9252	9252	9252	9252

Note: This table contains the Logit regression results of *DFII* on *ES*, with Column (1) reporting the univariate results and Column (2) reporting the results of the regression that includes the control variables. Columns (3) to (5) list results where three energy types (primary, transitional, and advanced energy) are used as the core dependent variable. Fixed effects include household-, region- and time-fixed effects. Clustered standard errors are reported in parentheses. *, **, and *** are significant at the 10 %, 5 %, and 1 % levels, respectively.

consumption. The results are presented in Columns (3)–(5) of Table 3. We found that digital finance had distinct effects on different kinds of energy. The impact of digital finance was negative for primitive energy types but significantly positive for transitional and advanced energy types. This suggests that digital finance reduces households' primitive energy use and gradually focuses their use on advanced energy sources. It also provides additional evidence that digital finance influences the structure of energy consumption and can result in the structural upgrading of household energy consumption, supporting our baseline conclusion.

5.2. Endogeneity and robustness

5.2.1. Endogeneity

The primary endogeneity concerns in this study were the omission of crucial variables and reverse causality. To address the former, we included crucial control variables in the regression; for the latter, we employed the instrumental variable method.

For instrumental variables, we select the number of post offices per million people in each city in 1984 multiplied by the previous year's national internet investment amount from the survey data (Nunn & Qian, 2014; Yadav et al., 2021) as the first proxy (*IV*1) and the distance between the household's regional location and Hangzhou city as the second proxy (*IV*2). These variables satisfy the conditions of exogeneity and relevance. Before the widespread popularization of the internet, postal services were an important means of communication for residents; therefore, regions with higher communication needs tended to have more developed postal networks. When the internet became widely available, these regions also achieved higher internet penetration rates, laying the foundation for the development of digital finance. Considering the time-varying nature of these factors, we multiplied the number of post offices per million people in each city in 1984 and the previous year's national internet investment amount from the survey data. In terms of independence, 1984 was over 40 years ago, well before the emergence and development of digital finance, and the national internet investment amount is less influenced by individual cities, meeting the requirements for the endogeneity of instrumental variables. IV2 is also a qualified proxy. As China's "capital of digital finance", the level of digital development in Hangzhou has spillover effects in other areas, but it is unlikely to affect the energy consumption choices of households in those regions (Wan, 2020). The F-statistics of the two IVs were sufficiently large, suggesting no weak instrument variable issue. As is shown in Table 4, the findings in Columns (2) and (4) confirm the benchmark model, reinforcing the robustness of the results.

5.2.2. Robustness check

We examined the robustness of the baseline regression using the following method. First, we excluded samples in Beijing, Shanghai, Tianjin, and Chongqing. These four cities are municipalities directly under the central government in China, with high levels of economic development and resident literacy, digital financial development, and resident use of digital financial services. The results when excluding the samples from these cities are presented in Column (1) of Table 5. Second, we employed the system-GMM using a one-period lagged term in the regression. The results are shown in Column (2) of Table 5. The test for the AR (1) effect rejected the null hypothesis of no first-order serial correlation, and the statistic of AR (2) was not significant. The Hansen test results also supported our conclusion.

To further strengthen our findings, we then applied a difference-in-difference (DID) method. We selected the Plan for Promoting Inclusive Financial Development (2016–2020) published in 2015 as the policy shock. Following Vig (2013) and Song et al. (2021), we divided the control and experimental groups as follows: we used the median of the level of digital financial development of the region in 2015 as the dividing criterion, and the samples above the median were classified as the control group ($Treat = 0$), while those below the median were labelled as the experimental group ($Treat = 1$). Samples from 2015 and earlier were labelled as 0 ($Post = 0$), and samples from 2016 and later were treated as 1 ($Post = 0$). The rationale for this division is that the policy aimed to promote growth in regions with poor digital finance development, and regions that were already more fully developed were not the target of the policy.

We use the following equation for the DID study:

$$ES_{ict} = \gamma_0 + \gamma_1 \bullet Treat_{ict} \bullet Post_{ict} + X'_{ict}\beta + \eta_i + \delta_c + \theta_t + \varepsilon_{ict} \tag{14}$$

Referring to Bertrand and Mullainathan (2003), we test the parallel trend by adding the interaction term of Treat and year dummy variable in the equation. The parallel trend results are shown in the first column (1) of the Table 6. We did not reject the assumption of prior trend parallelism. The coefficient in column (2) of Table 6 is also in line with the baseline regression, so our finding is robust.

5.3. Mechanism analysis

In Section 3.2, four hypotheses regarding the influencing mechanisms are proposed. In this part, referring to the method used by Zhao et al. (2025), we select proper mediating variables to verify whether the hypotheses are meaningful.

5.3.1. Infrastructure construction

The development of digital finance can drive the improvement of regional energy infrastructure, which provides the basis for households to choose advanced energy sources. For example, the prerequisite for households to choose piped natural gas is that the region has gas pipelines, and the prerequisite for households to choose solar energy is that they have installed photovoltaic panels and other solar energy equipment. Therefore, we selected the mediating variable of regional energy-related infrastructure investment expenditure (*Infra*).[4]

The results in Table 7 support **H2**, indicating that infrastructure construction is an effective mechanism. First, digital finance can accurately and quickly assess the risk and return characteristics of projects, helping financial institutions identify high-quality projects for credit support and promote project implementation. Further, green credit offers diversified financing options for photovoltaic, wind power, and other renewable energy projects. The mutual integration and promotion of technology and finance not only expand funding sources but also reduce financing costs. Second, digital finance breaks down the geographical and demographic barriers of traditional financial services, enabling dispersed social capital to directly connect with energy projects and support the implementation of distributed energy projects such as small-scale solar charging stations. The inclusive effects of digital finance promote the formation of a diversified investment landscape involving government, businesses, and society. Third, digital finance facilitates the payment of household bills, and this convenience allows infrastructure investors to quickly and easily receive income. This increases their investment enthusiasm and confidence, which are conducive to the improvement of infrastructure.

5.3.2. Household environmental literacy

The selected mediating indicator is the extent to which households agree that individuals have a very limited role to play in controlling energy consumption and improving the environment (Literacy).[5] Table 8 summarizes the results, which confirm **H3**.

A household's environmental literacy directly determines whether it has sufficient motivation to choose cleaner energy sources. A household with high environmental literacy will be willing and proactive in choosing clean energy to reduce environmental pollution and improve energy efficiency, even if such choices may result in increased energy expenses. A vivid example of this is the GoodLeap platform in the United States, which provides zero-down-payment photovoltaic loans to households. Users repay the loans through

[4] We used the length of the natural gas pipeline divided by the permanent resident population (in millions) in the area of the home as a proxy.

[5] Measured on a scale of 1 (strongly agree) to 5 (disagree), with higher values representing higher environmental literacy in the household.

Table 4
Endogeneity check.

Variables	*DFII*	*ES*	*DFII*	*ES*
	First stage	Second stage	First stage	Second stage
	(1)	(2)	(3)	(4)
DFII		0.0059***		
		(0.0022)		
IV 1	0.0233***			
	(0.0067)			
IV 2			0.0326***	
			(0.0094)	
Constant		17.623***		16.952***
		(0.891)		(0.967)
Controls	Yes	Yes	Yes	Yes
Adj-R^2	0.961	0.482	0.957	0.532
Observations	9252	9252	9252	9252
Cragg-Donald Wald F-statistic	–	15,209.43	–	15,136.58

Note: This table shows the results of 2SLS regression. Fixed effects are included in Controls.

Table 5
Robustness check.

Variables	*ES*	*ES*
	Sample excluding	System-GMM
	(1)	(2)
DFII	0.0077***	0.0089***
	(0.0036)	(0.0041)
Constant	20.173***	25.074***
	(3.783)	(4.899)
Controls	Yes	Yes
Adj-R^2	0.796	0.807
Observations	9252	9252
AR (1)		0.000
AR (2)		0.209
Hanson test		0.479

Table 6
DID results.

Variables	*ES*	*ES*
	Parallel trend test	DID
	(1)	(2)
*Treat*Post*		0.0674***
		(0.0219)
*Treat*year*2013	0.0037	
	(0.0093)	
*Treat*year*2014	0.0386	
	(0.1782)	
*Treat*year*2015	0.0573	
	(0.2906)	
*Treat*year*2018	0.0875***	
	(0.0249)	
Controls	Yes	Yes
Fixed effects	Yes	Yes
Adj-R^2	0.413	0.397
Observations	9252	9252

savings on electricity bills and tax credits while learning about the installation and operation of solar energy systems. In China, Da Jia Asset cooperates with farmers through a household photovoltaic fund. Farmers not only receive initial installation fees and long-term revenue sharing but also subtly improve their households' environmental awareness and experience the concrete advantages of advanced energy. Further, many applications, such as Alipay, have integrated energy management tutorials. When households pay their bills online, they receive environmental protection–related knowledge push notifications, followed by specific incentives, including virtual points that can be exchanged for gifts and vouchers that can be used to offset bills. These multiple incentives and the

Table 7
Mechanism analysis of infrastructure construction.

Variables	*Infra*	*ES*
DFII	0.0329***	0.0093***
	(0.0045)	(0.0033)
Infra		0.0237***
		(0.0095)
Controls	Yes	Yes
Adj-R^2	0.139	0.854
Observations	9252	9252

Table 8
Mechanism analysis of household environmental literacy.

Variables	*Literacy*	*ES*
DFII	0.0473***	0.0136***
	(0.0049)	(0.0048)
Literacy		0.0306***
		(0.0117)
Controls	Yes	Yes
Adj-R^2	0.217	0.879
Observations	9252	9252

inclusive nature of digital finance have advanced households' environmental literacy, thereby encouraging them to upgrade their energy consumption structure.

5.3.3. *Improved payment environment*

Traditional payment methods have limitations arising, for example, from the need to pay in cash or use a physical bank card. However, with the development of digital financial technology, electronic, mobile, and other convenient digital payment methods have become popular and are promoted, which may have positively impacted household energy consumption. We chose e-commerce sales divided by regional per capita consumption expenditure in the region as a proxy measurement for payment environment improvement (*Payment*). The regression results are presented in Table 9.

The significant positive coefficient of *DFII* × *Payment* suggests that **H4** is verified, indicating that digital finance contributes to the upgrading of household energy structures by improving their payment environment. This result is consistent with the economic reality. First, with the support of digital finance, households can more conveniently complete payments for their energy consumption, saving time and effort. Traditional payment methods may involve waiting in line, filling out cumbersome forms, or experiencing transfer delays. Digital payment methods, by contrast, make it easy to pay instantly, reducing the inconvenience of the payment process. Family members no longer need to physically go to the property management office or the bank to pay energy bills; they can simply touch their phone screen or scan a code to complete the payment. This greatly improves the payment experience and payment efficiency.

Second, digital finance offers households greater choice and flexibility in their energy consumption. With the advancement of digital payment technology, household energy consumers can choose from various payment methods, including electronic payment, prepaid cards, and virtual currencies, to suit their situation and preferences and better manage their energy consumption. Unlike primary energy, advanced energy can be integrated with digitalization. Digital finance also provides additional statistical and analytical tools that help households optimize their energy consumption structure. Through the digital payment system, households can access detailed energy consumption data and billing information to understand the details of their consumption, including their habits and preferences. These data can then be used to analyze and compare energy consumption over time, enabling users to formulate energy-saving plans and adjust the structure of their consumption accordingly. This data-driven management approach helps household energy consumers use energy resources more rationally and more naturally to realize the goal of upgrading their energy consumption structure.

Table 9
Mechanism analysis of improved payment environment.

Variables	*Payment*	*ES*
DFII	0.0279***	0.0076**
	(0.0058)	(0.0040)
Payment		0.0485***
		(0.0203)
Controls	Yes	Yes
Adj-R^2	0.303	0.811
Observations	9252	9252

5.3.4. Household risk-hedging ability

Digital finance has revolutionized the way households manage risks and uncertainties. By offering a wide range of risk management tools, digital finance enhances a household's ability to hedge against risks and alleviate uncertainty. This enables households to make more informed decisions regarding their choice of energy sources, with an increasing preference for advanced energy options. We verified this mechanism by introducing the regional internet insurance premium income divided by regional per capita consumption expenditure as a channel variable (*Insurance*).

The results presented in Table 10 confirm the positive and significant relationship. This finding supports **H5**, demonstrating that digital finance increased the use of online insurance in our sample, which is associated with a greater likelihood of households adopting advanced energy sources for consumption. In other words, an upgraded energy consumption structure is observed when households have access to digital-finance-backed insurance services.

Digital finance is crucial in enhancing the overall living standards of households by facilitating their access to insurance coverage. During uncertain times, households tend to reduce their spending and delay adjusting their consumption. Digital finance can overcome this barrier by making online insurance more accessible. By improving households' risk-hedging ability, digital finance promotes the upgrading of their energy consumption patterns. In summary, digital finance empowers households to effectively manage risks and uncertainties and, consequently, their energy consumption choices. Households' ability to transition to higher-quality energy usage as a result of digital finance and the increased insurance coverage it facilitates highlights the integral role of such finance in catalyzing sustainable energy consumption and improvements in household well-being.

5.4. Heterogeneity analysis

5.4.1. Regional comparison

There is significant regional variation across China's vast geographical expanse, including in natural conditions and social development. More specifically, regions exhibit distinct energy consumption characteristics due to factors such as climate, policies, the local economy, and resource endowments. In general, the northern areas experience lower temperatures during the winter, leading to higher heating demand. Additionally, the abundance of fossil fuels in the north means that households in these regions are more likely to rely on coal and other sources to meet their heating needs. Meanwhile, China's eastern regions tend to be more economically developed, with less energy-intensive industries, resulting in a greater demand for premium energy sources. We took these differences into account by dividing the sample into five regions: north, northeast, south, northwest, and east. The results are reported in Table 11.

In the northern and western regions of China, which have lower levels of economic development but relatively abundant energy resources, digital finance stimulated households' upgrading of their energy structures. In contrast, in the east and south, which have higher levels of economic development but relatively scarce energy resources, the effect was insignificant, possibly because of the regions' relatively advanced energy consumption structures. This serves as a reminder to regional administrators wishing to stimulate the upgrading of household energy structures that they should reasonably judge their region's energy structure and use suitable financial tools and policy measures.

5.4.2. Levels of government environmental attention

Government environmental attention (GEA) measures the level of attention given by local governments to environmental protection. In China, administrative power is centralized, and policies backed by the government tend to be implemented within a short period. Governments that attach importance to environmental issues generally adopt supportive policies and provide assistance in industrial planning, environmental protection investment, taxation, and financial subsidies. Governmental attention to the environment influences policy decisions, and the scale and flow of local fiscal funds determine the level of governmental environmental attention. The environmental landscape heavily shapes energy consumption patterns and may lead households to opt for higher-quality energy consumption. When the local government pays attention to environmental concerns, households are inclined to reduce reliance on traditional energy sources and promote a shift toward modern alternatives like electricity (Bao & Liu, 2022; Liu et al., 2023; Ocasio et al., 2018). Thus, the level of GEA affects the upgrading of household energy consumption: the government guides households in establishing a habit of using advanced energy by providing subsidies to promote household energy upgrading and introducing restrictive measures to reduce traditional energy use.

Drawing on several studies (Bao & Liu, 2022; Liu et al., 2023), we divided the samples into two categories based on the median value: higher GEA and lower GEA. To calculate GEA, we used keywords and word frequency in an analysis of policy documents related to environmental protection. Households in regions where the GEA exceeded the median value were sorted into the higher GEA group, and those in regions with lower GEA than the median were put in the lower-GEA category.

The results presented in Table 12 show that digital finance contributed to upgrading the structure of household energy consumption only in regions with higher GEA, suggesting that local governmental policy support is essential for the tools of digital finance to make a real difference.

5.5. Further study—an empirical test of energy stacking theory

Our results demonstrate that digital finance stimulates household energy consumption upgrading, which raises the following question: Does the upgrading process match energy stacking theory? Energy stacking theory posits that the upgrading of energy consumption is gradual and includes a transitional phase in which traditional and advanced energies coexist (Mgimba, 2017). We therefore tested the process of energy upgrading by Chinese rural households. First, we constructed the energy stacking variable

Table 10
Mechanism analysis of household risk-hedging ability.

Variables	*Insurance*	*ES*
DFII	0.0176*** (0.0055)	0.0247*** (0.0093)
Insuarance		0.0590*** (0.0861)
Controls	Yes	Yes
Adj-R^2	0.226	0.818
Observations	9252	9252

Table 11
Regional heterogeneity.

Variables	North	Northeast	South	Northwest	East
	(1)	(2)	(3)	(4)	(5)
DFII	0.108***	0.296***	0.016	0.281***	0.025
	(0.037)	(0.058)	(0.039)	(0.042)	(0.017)
Controls	Yes	Yes	Yes	Yes	Yes
Adj-R^2	0.502	0.446	0.569	0.461	0.495
Observation	1796	1008	3280	1252	1916
Suest test	(1)–(3)	(1)–(4)	(1)–(5)	(2)–(3)	(3)–(5)
Diff	−5.906	0.507	−0.831	−4.673	0.704
p-value	(0.0026)	(0.0042)	(0.0089)	(0.0033)	(0.1407)

Table 12
GEA heterogeneity.

Variables	Lower GEA	Higher GEA
	(1)	(2)
DFII	0.055	0.039***
	(0.080)	(0.006)
Control	Yes	Yes
Adj-R^2	0.579	0.593
Observations	4784	4468
Suest test	(1)–(2)	
Diff	0.407	
p-value	(0.0072)	

(*ESTA*) as follows. We divided the 12 energy types into three categories, as mentioned previously: primitive energy, transition energy, and advanced energy. *ESTA* was assigned a value based on the type of fuel involved in the household's energy consumption.[6] *ESTA* thus measured energy mixing in households. Second, we introduced the number of energy types consumed by the household (*ET*) to reveal the amount of energy used by the household at the same time. The empirical results are shown in Table 13.

The positive significant coefficient in Column (1) of Table 10 indicates that the development of digital finance was accompanied by a trend toward energy mixing in households. In Column (2), the square of the DFII was included to capture the nonlinear effect (Ai et al., 2021), and the coefficient is significantly negative, suggesting that the development of digital finance led to an initial increase and then a decrease in the number of types used by households at the same time. The results in Table 10 thus verify that the energy consumption upgrading of the households is consistent with the energy stacking theory rather than the energy ladder theory. When digital finance began to develop, households opted for traditional energy sources; later, with the digital dividends of digital finance's advancement, households' energy choices will be upgraded gradually. This shows that energy upgrading takes time. Therefore, when promoting energy upgrades in households, it is necessary to take into account the reality of energy stacking, avoid one-size-fits-all policies, and allow for transitional periods.

6. Conclusion and discussion

This study considered the nexus between digital finance and the upgrading of household energy structures. Using data from the

[6] *ESTA* = 1 if the household used only primary energy, *ESTA* = 2 if the household used a mix of primary and transition energy, *ESTA* = 3 if the household used only transition energy, *ESTA* = 4 if the household used a mix of transition and advanced energy, and *ESTA* = 5 if the household used only advanced energy.

Table 13
Test of energy stacking theory.

Variables	*ESTA*	*ET*
	(1)	(2)
DFII	0.048***	0.034***
	(0.009)	(0.007)
DFII^2		−0.003***
		(0.0007)
Constant	7.560***	19.052***
	(0.407)	(0.621)
Control	Yes	Yes
Adj-R^2	0.571	0.548
Observations	9252	9252

DFII, CRECS, and CGSS databases, we empirically validated our hypotheses. Our findings indicate that digital finance stimulates energy consumption upgrading through infrastructure construction, increased household environmental literacy, improved payment environments, and enhanced risk hedging ability. We also found that energy consumption is upgraded through the co-existence of several energy types; in other words, upgrading energy consumption is a process of supplementation rather than substitution, in line with the phenomenon of energy stacking. Our study provides the following insights.

First, household energy consumption upgrading is achieved with the help of digital finance. Accordingly, governments should consider further developing digital finance as a crucial policy tool for boosting household consumption. Notably, the government should improve the infrastructure required for digital finance and continuously improve the recognition and acceptance of digital financial tools by households and individuals so that the digital dividends can be more fully and broadly enjoyed.

Second, governments wishing to harness the positive effects of digital finance on household energy consumption should pay attention to transmission mechanisms and related influencing factors. Digital finance supports household energy upgrades through channels that ease liquidity constraints and improve the convenience of payments and households' ability to take risks. The facilitation of these channels requires the effort of multiple parties. Households should recognize the role of digital finance in this, and governments should regulate its development and avoid the negative impacts of blind expansion. This involves refining online loan regulations and facilitating convenient payment methods and a better consumption environment.

Third, governments should tailor digital finance developments to the specific economic conditions and natural endowments of different regions to take advantage of the potential of digital finance. Furthermore, environmental protection and sustainable development should be considered to create an environment conducive to energy consumption upgrades.

Finally, we provided new evidence supporting the energy stacking theory. This implies that a one-size-fits-all approach is inappropriate in the process of fostering household energy upgrading. Efforts should instead be grounded in the reality that a mix of energies is involved in the upgrading process and facilitate a gradual transition to advanced energies for household energy use.

Due to data availability limitations, we have not taken the application of new energy sources into account. Moreover, given the lasting negative impact of the COVID-19 pandemic on the global economy, it is unclear whether this structural change will shift the role played by digital finance in upgrading household energy structures. We look forward to future research delving into these issues.

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Appendix A. Proof of Eq. (10)

From the basic model, by doing the first order condition, we can get the following equations.

$$\frac{Y_t}{N_t} = \frac{\tau}{\beta^k(1-\alpha)} \tag{A-1}$$

$$\beta E_t \frac{1}{C^1_{t-1}}\left[\alpha\frac{Y_{t+1}}{K_t} + 1 - \delta\right] = \frac{1}{C^1_t} \tag{A-2}$$

$$\beta E_t \frac{1}{\tau(1-N_{t+1}) + C^2_{t+1}}\left[\alpha\frac{Y_{t+1}}{K_t} + 1 - \delta\right] = \frac{1}{\tau(1-N_t) + C^2_t} \tag{A-3}$$

$$C^1_t + C^2_t + K_t = Y_t + (1-\delta)K_{t-1} \tag{A-4}$$

$$Y_t = A_t^{1-\alpha} K_{t-1}^{\alpha} N_t^{1-\alpha} \tag{A-5}$$

$$\log A_t = \rho \log A_{t-1} + u_t \text{ and } u_t \sim N(0, \sigma_u) \tag{A-6}$$

Find the steady state:

$$A = 1 \tag{A-7}$$

$$\frac{\mathrm{Y}}{\mathrm{N}} = \frac{\tau}{\beta^k(1-\alpha)} \tag{A-8}$$

$$\frac{Y}{K} = \frac{\left[\frac{1}{\beta} - (1-\delta)\right]}{\alpha} \tag{A-9}$$

$$\begin{aligned} \frac{C' + C^2}{Y} &= 1 - \delta\frac{K}{Y} \\ &= 1 - \frac{\delta\partial}{\frac{1}{\beta} - (1-\delta)} \end{aligned} \tag{A-10}$$

$$\frac{C_t^1}{\tau(1-N_t) + C_t^2} = 1 \tag{A-11}$$

$$\begin{gathered} C^1 = \tau(1-N) + C^2 \\ C^1 + C^2 = \tau(1-N) + 2C^2 \\ 1 = \frac{\tau(1-N)}{C^1 + C^2} + 2\frac{C^2}{C^1 + C^2}\frac{C^2}{C^1 + C^2} = \frac{1}{2}\left[1 - \frac{\tau(1-N)}{C^1 + C^2}\right] = \frac{1}{2}\left[1 - \frac{\frac{\tau(1-N)}{Y}}{\frac{(C^1 + C^2)}{Y}}\right] \end{gathered} \tag{A-12}$$

Data availability

Data will be made available on request.

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