# The optimization Pathways for Rural Heating Energy Structure Empowered by Rural Revitalization: A Survey of 367 Farmer Households in Zhang County, Gansu Province

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**Abstract.** In the early 21st century, Gansu Province in China adopted a coal-dominated heating system. However, this method not only posed significant safety risks but also proved detrimental to environmental protection. In recent years, in response to national policies such as the Rural Revitalization Strategy and the Dual Carbon Goals, the province has actively promoted clean heating initiatives, though with limited effectiveness. Therefore, this study selected Zhang County—one of the ten most impoverished counties in Gansu—as a case study site for sample-based investigation. A total of 367 questionnaires were collected and analyzed to identify the key factors influencing the reform of heating energy sources and to propose relevant policy recommendations. Through methods such as data collection, the study first clarifies the advantages and disadvantages of clean energy sources such as solar power. Descriptive analysis reveals the major challenges facing heating energy reform in Gansu Province. Subsequently, a regression model was constructed using variables such as heating satisfaction and the perceived importance of energy reform. The results indicate that, in addition to economic and environmental factors, the government should also prioritize improving public awareness of heating energy reform to enhance public support. Finally, proposes an innovative heating model combining biomass, hydropower, and air energy. This model not only demonstrates high environmental and economic efficiency but also improves comfort and convenience, offering practical guidance for energy reform in Gansu Province.

**Keywords:** Optimization of heating energy structure; rural revitalization; health; green energy


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# 1 Introduction

## 1.1 Research Background

The 2018 National Bureau of Statistics report indicates that carbon-intensive fuels accounted for 57.7% of China's total energy consumption and 71.1% of total energy use, with power generation and heating constituting 41.7% of China's final energy consumption, predominantly supplied by fossil fuels[1]. On September 22, 2020, China formally proposed its "Dual Carbon" targets at the 75th UN General Assembly, aiming to achieve carbon peak by 2030 and carbon neutrality by 2060. General Secretary Xi Jinping stated at the 20th National Congress of the Communist Party of China: "In the new era of socialism with Chinese characteristics, we must adhere to the concept that lucid waters and lush mountains are invaluable assets, and we must promote historic, transformative, and comprehensive improvements in ecological and environmental protection." Against this backdrop, although Gansu Province has actively advanced clean heating initiatives, the proportion of clean energy used for heating remains low. Rural areas still rely on coal-fired stoves, heated brick beds, and electric blankets, which result in high heating costs, low combustion efficiency, and significant pollutant emissions. Moreover, coal-based heating presents considerable safety risks. The World Health Organization and the United Nations Development Programme have issued a joint statement noting that approximately 1.6 million people in developing countries die each year due to the incomplete combustion of fuels[2]. Zhang County in Gansu is a key national poverty-alleviation county, where only 1.22% of households use clean energy for heating[3], and its heating practices largely reflect the provincial norm. Therefore, using Zhang County as a case study to explore feasible pathways for optimizing heating energy structures holds strong practical significance and can effectively contribute to the realization of the Rural Revitalization Strategy and the Dual Carbon Goals.

## 1.2 Research Objectives and Significance

This study aims to address heating issues and demands in rural areas of Gansu Province through the optimization of heating energy structures. The main research objectives are as follows: First, to reduce energy consumption and improve energy efficiency through technological upgrades and improved operational management; Second, to explore the use of renewable energy sources such as solar, hydro, and biomass energy, thereby reducing dependence on traditional non-renewable energy and mitigating environmental pollution; Third, to enhance safety by upgrading protective infrastructure and standardizing operational procedures; Fourth, to promote cost-effective heating methods that lower household expenditures, increase disposable income, and support related industries;Fifth, to provide a theoretical and empirical basis for heating energy structure reform in Gansu Province, offering policy recommendations to accelerate the transition to green energy and avoid resource waste.

# 2 Current Situation and Analysis of Clean Energy

## 2.1 Solar Energy

Solar heating utilizes solar collectors to convert solar energy into thermal energy. While offering advantages like renewability, energy savings, and cost-effectiveness, it faces limitations including weather dependency, immature heat storage technology (both short-term and seasonal storage), system instability, and high installation/maintenance costs. Recent international research has focused on heat storage, with short-term storage studies examining solar phase-change heat storage water systems and phase-change solar heating systems, as well as analyzing the efficiency of solar collectors, heat storage tanks, and solar fraction under different collector areas and tank volumes[4-6] .Seasonal storage research emerged later, including Fernqvist et al's (2004) cost comparison between aquifer storage and buried pipe storage[7]. Additionally, Zhao Yaqi et al. (2022) introduced IoT modules and sun-tracking algorithms to solar collector systems, achieving 40% more heat absorption while reducing installation costs by 30%. Solar collectors experience heat loss (QL) consisting of three components: top loss, edge loss, and bottom loss，that is to say, $Q_L = A_t U_t (t_p - t_a) + A_e U_e (t_p - t_a) + A_b U_b (t_p - t_a)$，Where $t_p$ represents the temperature of the heat-absorbing plate; $t_a$ denotes the ambient (air) temperature; $A_t$ and $U_t$，$A_e$ and $U_e$, $A_b$ and $U_b$ correspond to the heat dissipation areas and heat loss coefficients of the solar collector's top, edges, and bottom respectively[8].

## 2.2 Biomass Energy

Biomass heating utilizes renewable materials (e.g., wood, crop residues) for thermal energy supply, offering advantages such as sustainability, environmental friendliness, and cost-effectiveness. It significantly reduces carbon emissions while leveraging abundant local resources. However, challenges include low-level pollutant emissions and logistical complexities in fuel storage and utilization. Among biomass heating methods, kang (traditional heated bed) systems are most prevalent, though they suffer from uneven surface temperature distribution. Zhang et al. (2024) addressed the issues of uneven temperature distribution and insufficient heat storage capacity in kang by employing phase change materials (PCMs)[9].

## 2.3 Hydroelectric Power

Hydronic heating utilizes water as a heat-transfer medium, storing thermal energy and distributing hot water through pipelines to provide space heating. This system demonstrates high heat transfer efficiency, uniform temperature distribution, and zero direct emissions, with compatibility for integration with other renewable energy sources. However, its implementation faces challenges including system complexity and leakage issues.

### 2.4 Electric Energy

Electric heating converts electrical energy into thermal energy through devicesto provide space heating. This system offers advantages including easy installation, noise-free operation, adjustable temperatures, and environmental cleanliness. However, energy conversion losses occur during operation, and in China's context, 55% of electricity was generated from coal combustion in 2021, resulting in substantial carbon emissions.

Yi et al. [10]developed an evaluation framework for rural electric heating suitability, incorporating six primary indicators (economic, technical, practical, comfort, safety, and environmental benefits) with subordinate secondary indicators. The assessment yielded a score of 6.945 (on a 10-point scale), demonstrating favorable acceptance among rural residents.

## 3 Investigation Result

### 3.1 Overview of Rural Areas in Zhang County

Following the Rural Revitalization Strategy proposed by the CPC Central Committee in 2017, various substantive policies have been gradually implemented across provinces and cities. With continuous advancements in science and technology, rural residents' living standards have significantly improved, leading to notable changes in household heating equipment and fuel sources. The traditional honeycomb coal stoves have evolved into oven-equipped stoves, and further upgraded to double-burner stoves with ovens. Regarding fuel sources, due to government winter subsidies, the proportion of firewood in heating fuels has substantially decreased, with coal becoming the predominant heating fuel. However, incomplete combustion of coal and firewood releases harmful gases such as CO, as well as environmentally polluting CO2 and NO2, exacerbating the greenhouse effect. In addition to stove heating, the electricity price for rural household users in Zhang County has been reduced from 0.54 yuan/KWH to 0.4 yuan/KWH, which reduces the cost of heating in winter to a certain extent and has a high cost performance. Therefore, optimizing rural heating energy structures is crucial not only for Zhang County's rural areas but also for rural regions nationwide and global climate and environmental sustainability.

### 3.2 The Drawbacks of Traditional Heating Fuels

In terms of human health.The combustion of coal and firewood releases substantial amounts of hazardous substances and particulate matter, including sulfur dioxide ($SO_2$), particulate matter (PM), carbon monoxide (CO), and nitrogen oxides ($NO_x$). Chronic exposure to these pollutants leads to the development and exacerbation of respiratory and cardiovascular diseases. According to 2022 data from the World Health Organization (WHO), approximately 6.65 million people worldwide die annually from exposure to ambient air pollution, including 4.24 million deaths related to household air pollution. Among these, over 200,000 fatalities are caused by carbon monoxide poisoning resulting from incomplete coal combustion[11].

In terms of environmental protection.The harmful substances and particulate matter emitted from coal and firewood combustion contribute to acid rain formation, causing severe damage to soil, water sources, and vegetation, while also leading to smog and air pollution. Data from China's Ministry of Natural Resources indicates that coal combustion releases approximately 25.49 million tons of sulfur dioxide annually, accounting for 90% of China's atmospheric pollution[12]. The International Energy Agency (IEA) reported in its 2023 Carbon Emissions Report that China's carbon emissions increased by about 565 million tons in 2023, reaching 12.6 billion tons of $CO_2$ equivalent[13]. In comparison, each tree can absorb merely 4-18 kg of carbon dioxide annually.

In terms of heating efficiency.Field experiments were conducted under controlled conditions: a 150-day heating season (October 15 to March 15), with daily tests from 8:00 AM to 8:00 AM the following day while maintaining indoor temperatures at 18-22°C. Results showed that 29 kg of standard coal was required daily to adequately heat a 175 $m^2$ dwelling. This translates to a seasonal requirement of 4,350 kg of bituminous coal, costing 5,220 RMB at current market prices (1,200 RMB/ton). Replacing coal with clean energy alternatives could potentially save over 100 million tons of coal annually, reduce carbon emissions by more than 250 million tons, and fundamentally address the inefficiency of rural heating systems in northern China.

### 3.3 A Successful Case of Clean Energy Reform

On June 6, 2022, the first pilot "solar-biomass" clean heating system was successfully tested at a residential property in Xizhang Village, Chaona Town, Lingtai County, Pingliang. The system configuration comprises: all-glass vacuum solar tubes, polyurethane-insulated stainless steel water tanks, low-emission biomass boilers, and steel radiators. The system utilizes big data control and IoT-based management to effectively integrate solar and biomass energy, addressing both year-round domestic hot water needs and clean winter heating demands. According to calculations, each household can replace traditional coal consumption with solar energy + 1.5 tons of biomass fuel annually, equivalent to 3 tons of standard coal. This reduces emissions by 4.6 tons of $CO_2$, 0.03 tons of $SO_2$, and 0.012 tons of NOx per year. Additionally, households save over 2,000 RMB annually, demonstrating significant energy-saving effects, economic benefits, and positive social impact[14].

## 4 Survey Design and Empirical Analysis

### 4.1 Questionnaire Design and Pilot Survey

Based on the research objectives, the questionnaire was divided into several sections, including basic demographic information of respondents; current heating conditions in the three provinces (heating method, satisfaction level, expenditure, existing problems, and pollution degree); directions for optimizing the heating energy structure (public support for reform, clean energy preferences, optimization strategies and their significance); and the influence of governmental policies (understanding of the Dual Carbon Goals and Rural Revitalization, perceived importance of energy reform, and policy-making directions).

To verify the standardization and reliability of the questionnaire, a pilot survey was conducted online prior to the formal data collection. A total of 50 questionnaires were distributed and retrieved from rural residents in Gansu Province. Based on the results, questions with unclear wording or inaccurate types were revised to ensure the questionnaire's validity.

## 4.2 Sample Size Determination

As the exact number of rural households was not available, the calculation was based on an average of four persons per household. According to the seventh national population census, the rural population of Zhang County in Gansu Province is approximately 113,400, i.e., N = 113,400. A random sample was selected, with a margin of error (d) not exceeding 5% and p set at 0.5. At a 95% confidence level, the required sample size was calculated using formula (1). The resulting sample size was n = 384.

$$n = \frac{u^2 p(1-p)}{d^2} \tag{1}$$

To ensure questionnaire validity, a total of 400 questionnaires were distributed. Quota sampling was conducted based on the rural population distribution in Zhang County. Details are presented in Table 1:

**Table 1.** Proportion of Rural Population and Questionnaire Distribution.

| Town(number) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | sum |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Rural Population (10,000) | 2.14 | 1.55 | 1.53 | 1.14 | 1.0<br>3 | 0.91 | 0.84 | 0.75 | 0.75 | 0.7 | 11.34 |
| Questionnaires Distributed | 75 | 55 | 54 | 40 | 36 | 32 | 30 | 26 | 26 | 25 | 400 |
| Proportion (%) | 18.9 | 13.7 | 13.5 | 10 | 9 | 8 | 7.4 | 6.6 | 6.6 | 6.3 | 100 |

A total of 400 questionnaires were distributed, and after a preliminary screening process to exclude invalid responses, 367 valid questionnaires were retained. The effective response rate was 91.75%.

## 4.3 Reliability and Validity Analysis

To verify the stability and reliability of the questionnaire used in this study, Cronbach's alpha coefficient was adopted for the reliability analysis. As shown in Table 2, the Cronbach's alpha coefficient of the questionnaire is 0.784, which is higher than 0.7 and close to 0.8, indicating good reliability. This suggests that the questionnaire is both reliable and stable. Subsequently, a validity analysis was conducted. The results showed a KMO value of 0.784, which is greater than 0.75, indicating high validity. This means that the content of the questionnaire aligns closely with the responses provided by the participants.

**Table 2.** Cronbach's Alpha Reliability Analysis.

| AlphaCronbach's Alpha | AlphaCronbach's Alpha Based on Standardized Items | Number of Items (Single-choice) |
|---|---|---|
| .784 | .802 | 7 |

## 4.4 Descriptive Analysis

SPSS 27.0 was used to conduct descriptive statistical analysis on the relevant items. Include maximum, minimum, mean, and standard deviation for each item. The average satisfaction with the current heating methods is 2.78 (Between 1~5), which is lower than the mid-point of the scale, indicating a relatively low satisfaction level. The perceived importance of energy reform has a mean of 3.77 (Between 1~5), close to 4, suggesting that most respondents consider energy reform to be of great significance. Among the shortcomings of the current heating methods, environmental pollution is the most serious, with a mean value of 0.68 (Between0~1). In terms of energy reform directions, expenditure reduction receives the most attention, while safety receives the least. Regarding government policies, subsidies or incentive programs are the most welcomed among respondents.

## 4.5 Lasso Regression Analysis

To explore the influencing factors of public support for energy reform (Y), this study considers heating satisfaction (Z) and the perceived importance of energy reform (I) as independent variables, while incorporating government policies and subsidies as control variables. Based on the questionnaire structure and logical framework, the following regression model is established:

$$Y_i = \alpha_1 Z_i + \alpha_2 I_i + \phi_i \tag{2}$$

A regression analysis based on this model was conducted, and the results are shown in Table 3:

**Table 3.** Lasso Regression Analysis Results.

| | Non-standardized coefficient B | standard error | Standardization coefficient B | t | p |
|---|---|---|---|---|---|
| constant | 2.360 | .237 | - | 9.945 | <0.001 |
| Temperature satisfaction | -.179 | .161 | -.183 | 3.313 | .009 |
| Energy reform significance | .532 | .052 | .573 | 4.459 | .017 |
| $R^2$ | | .164 | | | |
| Adjust the $R^2$ | | .158 | | | |
| F | | F (1,365)=26.949,p =0.001 | | | |

As shown in Table 3, the model passes the F-test ($F = 26.949$, $p = 0.001 < 0.05$), indicating that the regression equation: $Y = 2.360 - 0.179Z + 0.532I$ is statistically significant. Both heating satisfaction (Z) ($t = 3.313$, $p = 0.009 < 0.05$) and the importance of energy reform (I) ($t = 4.459$, $p = 0.017 < 0.05$) have significant effects on support for energy reform (Y), suggesting that Z and I are influential factors.

To further investigate the driving forces behind the variation in heating satisfaction (Z), a new regression model (Equation 4) was constructed, in which heating expenditure (E) and deficiency levels of current heating methods (D) (specific items include High Cost, Severe Environmental Pollution, Poor Heating Performance, Inconvenience of Use and Major Safety Hazards) were used as independent variables.

$$D = \sum_{i=m}^{n} D_i \tag{3}$$

$$Z = \delta_i + \beta_1 E_i + \beta_2 \sum_{i=m}^{n} D_i \tag{4}$$

A regression analysis based on this model was conducted, and the results are presented in Table 4:

**Table 4.** Regression Analysis Results.

| | Unstandardized Coefficient | | Standardized Coefficient | t | p |
|---|---|---|---|---|---|
| | B | Standard Error | Beta | | |
| Constant | 2.338 | 0.287 | - | 8.154 | 0.000** |
| D | -.154 | .073 | -.148 | 2.110 | 0.036* |
| E | 0.310 | 0.082 | 0.264 | 3.763 | 0.001* |
| R2 | | 0.527 | | | |
| Adjusted R2 | | 0.521 | | | |
| F | | F (2,63)=9.510,p=0.001 | | | |
| Durbin-Watson Statistic | | 1.0416 | | | |

According to Table 4, the model ($F=9.510$, $p=0.001 < 0.05$) passes the F-test, and the equation is $Z=0.310E-0.154\sum_{i=m}^{n} D_i +2.338$. The model indicates that the effectiveness of the heating method is negatively correlated with the defect level of the heating method (D), and positively correlated with the heating expenditure (E). As D decreases and E increases, the heating effectiveness improves. This suggests that villagers tend to prefer heating methods that are economical, environmentally friendly, and efficient in heating performance.

Combining Equation (1) and Equation (3), the regression equation model (4) is obtained: $Y=0.532I-0.056E+0.028\sum_{i=m}^{n} D_i +1.94$. According to this equation, the regression coefficient of the importance of energy reform (I) is significantly greater than that of heating expenditure (E) and defect level of the heating method (D), indicating that the government should pay more attention to public awareness and emphasize the importance of energy reform. This can help change residents' attitudes toward energy reform and increase their support for the clean transition of heating energy.

# 5 Innovative Heating Method: Biomass Energy + Hydropower + Air Energy

## 5.1 Overview of Heating Methods

In Zhang County's rural areas, biomass energy remains the primary heating source. So we propose an integrated "biomass + hydro + aerothermal" heating system implemented through the following upgrades: First, rock wool panels are installed for exterior wall insulation, while traditional heated beds (kang) are converted into hydronic heated beds using galvanized aluminum-zinc alloy sheets, eco-friendly polyurethane foam, PERT underfloor heating pipes, and copper fittings[15]. Second, a heat conduction circulation system is embedded within the bed structure, featuring drilled perforations beneath the apex point with installed thermal insulation covers, complemented by aerothermal heating equipment. Additionally, smart controllers paired with temperature sensors enable automated climate control, while retaining the biomass combustion chamber beneath the bed with added iron dampers to regulate smoke emission. The upgraded system delivers high efficiency with low emissions and uniform heat distribution, with the rock wool exterior walls providing additional corrosion resistance and structural reinforcement.

## 5.2 Analysis of Heating Methods

The rock wool panel retrofit reduces heat loss while providing corrosion and earthquake resistance. The hydronic heated bed (kang) solves uneven heating issues, with polyurethane materials maintaining constant water temperature. Steam transfer in thermal insulation covers, combined with aerothermal equipment, enables whole-house heating, while smart temperature control enhances comfort. This solution suits Zhang County's rural areas because: 1) Universal tap water ensures hydro heating convenience; 2) Abundant biomass (crop straws, etc.) provides near-zero-cost fuel; 3) The high upfront cost of aerothermal units (¥9,000/unit) requires technological improvements or government subsidies to improve affordability.

## 5.3 Feasibility Analysis of Heating Methods

Based on online data, China's discount rate from 2007 to 2024 ranged between 11%-13%, with 12% selected as the median value. The aerothermal heater has a 15-year lifespan, and the average household area in Zhang County is 175 $m^2$. NPV/IRR analysis was conducted for both coal , solar energy + coal and new heating systems.

Coal heating solution: Maintaining 18°C requires 29 kg of standard coal daily, totaling 4,350 kg of bituminous coal per winter (at 1,200 yuan/ton), resulting in annual costs of 5,220 yuan. The coal stove costs 500 yuan/unit (5-year lifespan, 50 yuan salvage value). Calculate using the formula of net present value NPV=-¥37199.83 NPV=$\Sigma A_n(\mathrm{P/A}, 12\%, \mathrm{n})$.

For the solar + coal heating method, to maintain an indoor temperature of 18°C, approximately 17.5 $m^2$ of solar collector panels are needed, priced at 180 yuan/$m^2$. The average installation cost of a solar collector is 8200 yuan/unit, with a residual value of 500 yuan and an annual maintenance cost of 800 yuan. Due to the significant influence of weather and environmental factors on solar energy, solar heating is unavailable for a certain period each winter. During this time, coal is used as a substitute, with an annual consumption of approximately 1 ton at a price of 1200 yuan/ton. The stove costs 500 yuan/unit, has a lifespan of 5 years, and a residual value of 50 yuan/unit. The calculated Net Present Value (NPV) is -26,148.96 yuan.

For the innovative heating system, market research shows the aerothermal heater installation costs ¥9,000 (salvage value ¥1,000) with annual maintenance of ¥300. Maintaining 18°C requires 100 kWh/month (¥0.46/kWh, 5 months), totaling ¥230/year in electricity. Rock wool panels (380㎡ at ¥10/㎡) cost ¥3,800, hydronic system modification materials ¥1,200, with zero-cost biomass fuel. Initial NPV calculation yields -¥15,559.88.

As the essence of winter heating lies in a comfortable living environment, which is difficult to quantify, we assume that such comfort helps prevent disease and thus saves on medical expenses. Assuming all three heating methods offer the same level of comfort, and the NPV of the "coal" heating method is set to 0, the avoided annual medical expenses due to comfort are estimated at 5462 yuan. Based on these assumptions, the NPV of solar + coal heating is NPV1 = 7066.17 yuan, with an Internal Rate of Return (IRR) of 20.94%; the NPV of the innovative heating method is NPV2 = 17,655.25 yuan, with an IRR of 34.86%. At this point, both heating methods have positive NPVs and IRRs greater than the discount rate (r), indicating that both are economically viable under the assumptions. However, since NPV2 > NPV1, the innovative heating method demonstrates greater economic feasibility. Compared to the current heating method, the innovative approach increases disposable income by 17,655.25 yuan over 15 years, thereby improving both income and quality of life without causing pollution.

### 5.4 Economic Value and Social Value

The innovative heating method is proposed based on the context of rural areas in Gansu Province, reflecting regional characteristics. At present, solar energy accounts for only about 5% of the market share in Gansu, with 95% still occupied by traditional heating methods. However, due to increasing public environmental awareness, supportive government policies, technological advancements, and concerns about energy security, clean energy is gaining increasing attention. It is expected to maintain strong growth in the coming years. The major challenges facing the promotion of solar heating in rural Northwest China include high initial investment, after-sales service issues, and lack of consumer trust due to its low market share. The innovative heating method proposed in this study not only utilizes green energy and actively responds to the national call for green development but also leverages the accessibility of rural water resources and the zero-cost nature of biomass fuel. Thus, it represents a positive response to the rural revitalization strategy and has strong potential for scalability.

## 6 Conclusions

Based on the survey and analysis of rural areas in Gansu Province, the following four conclusions are drawn: First, clean energy sources such as solar energy are not highly feasible for heating energy reform in rural areas of Gansu Province. Second, residents' satisfaction with current heating methods is below average, with major disadvantages including severe environmental pollution, high cost, and poor heating effectiveness. Third, in the context of energy reform, residents are most concerned about heating expenditure and government subsidies. Fourth, compared to the disadvantages of current heating methods, the importance of energy reform has the most significant impact on support for heating energy transition.

Based on the above conclusions, the following four recommendations are proposed to promote the clean transition of heating energy: First, select clean energy sources according to local conditions. In promoting heating energy reform, the government should consider the specific characteristics of local rural areas and choose the most suitable one or more clean energy sources. Second, optimize the heating structure. Clean energy heating should avoid the issues that lead to low satisfaction with current methods by improving heating safety, affordability, and related influencing factors. Third, increase government subsidies. Through subsidies or incentive policies, the government can reduce residents' heating costs, thereby enhancing their enthusiasm and support for heating energy reform. Fourth, the government should focus more on public awareness of heating energy reform. Through outreach efforts, residents can better understand the importance of the reform, thus increasing support for clean heating energy in rural areas.

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