Occurrence Conditions of Shallow Geothermal Energy and Suitability Analysis of Ground-Source Heat Pump Systems in Lanzhou New Area (Postprint)

Authors: Fan Bin

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Abstract

The development and utilization of shallow geothermal energy facilitates the optimization of regional energy structure, conservation of conventional fossil energy, and reduction of CO_2 emissions. To characterize the suitability features of shallow geothermal energy in Lanzhou New Area and provide a scientific basis for development planning of such resources and government decision-making, this study takes the built-up areas and planning areas of Lanzhou New Area as the research object. Based on the analysis of shallow geothermal energy occurrence conditions in the region, and relying on acquired multi-year actual exploration data and test data, a suitability evaluation analysis of soil-source heat pump systems was conducted for the 440 km^2 area of Lanzhou New Area through comprehensive application of improved Analytic Hierarchy Process (AHP) and comprehensive index method. The results indicate that: (1) Lanzhou New Area possesses relatively excellent shallow geothermal energy occurrence conditions, with simple and stably distributed stratigraphic structure, and relatively high comprehensive thermal conductivity, specific heat capacity, and geothermal gradient of the rock-soil mass, which are highly favorable for the application of soil-source heat pump systems; however, due to factors such as weak aquifer water abundance and poor water quality, the suitability of groundwater-source heat pump systems is poor. (2) The suitability evaluation model established based on Analytic Hierarchy Process comprises 3 attribute criteria and 7 factor indicators, uses exponential scale to construct judgment matrices at each level, all of which passed the consistency test with high precision, while optimizing the dimensionless method for each factor parameter, making the constructed evaluation model more realistic. (3) The factors with significant influence on the suitability of soil-source heat pumps in the study area are mainly average thermal conductivity and geothermal gradient. The evaluation shows that the total area of suitable and relatively suitable zones for soil-source heat pump systems in Lanzhou New Area is 359.46 km^2, accounting for 81.70% of the total evaluation area, mainly distributed in the plain area of Qinwangchuan Basin, while the remaining hilly and mountainous areas are unsuitable for the construction of soil-source heat pump systems. The evaluation results provide guidance for the development and utilization planning of soil-source heat pump systems in Lanzhou New Area and even in other regions with similar geological conditions.

Full Text

Occurrence Conditions of Shallow Geothermal Energy and Suitability Analysis of Soil Source Heat Pump Systems in Lanzhou New District

FAN Bin1,4, **DING Hongwei**2, **ZHANG Linxin**1,4, **ZHANG Lingpeng**1,4, **ZHANG Yongjun**3,4

1 The Second Institute of Geology and Minerals Exploration, Gansu Provincial Bureau of Geology and Minerals Exploration and Development, Lanzhou 730020, Gansu, China
2 Gansu Provincial Bureau of Geology and Minerals Exploration and Development, Lanzhou 730000, Gansu, China
3 Gansu Geological Environment Monitoring Institute, Lanzhou 730050, Gansu, China
4 Gansu Provincial Key Laboratory of Groundwater Engineering and Geothermal Resources, Lanzhou 730050, Gansu, China

Abstract: The development and utilization of shallow geothermal energy contributes to optimizing regional energy structure, conserving conventional fossil fuel resources, and reducing carbon emissions. Mastering the suitability characteristics of shallow geothermal energy in Lanzhou New District provides a scientific basis for resource development planning and government decision-making. This study examines both the built-up and planned areas of Lanzhou New District as the research object. Based on an analysis of shallow geothermal energy occurrence conditions and drawing upon extensive actual exploration data and test measurements covering 440 km^2 over many years, we conducted a suitability evaluation for soil source heat pump (SSHP) systems using an improved analytic hierarchy process (AHP) combined with the comprehensive index method. The results demonstrate that: (1) Lanzhou New District possesses excellent shallow geothermal energy occurrence conditions, featuring a simple and stable stratigraphic structure, high comprehensive thermal conductivity of rock-soil mass, high specific heat capacity, and relatively high geothermal gradient—all highly favorable for SSHP application. However, due to factors such as weak aquifer productivity and poor water quality, groundwater source heat pump systems show poor suitability. (2) The established suitability evaluation model comprises three attribute criteria and seven element indexes. Using an index scale, judgment matrices were constructed at each hierarchical level, all passing consistency tests with high precision. Simultaneously, the dimensionless processing method for each parameter was optimized, yielding an evaluation model that better reflects reality. (3) The primary factors influencing SSHP suitability in the study area are average thermal conductivity and geothermal gradient. The evaluation reveals that suitable and relatively suitable zones for SSHP systems in Lanzhou New District cover a total area of 359.46 km^2, accounting for 81.70% of the evaluation area. These zones are mainly distributed in the plain area of Qinwangchuan Basin, while hilly and mountainous regions are unsuitable for SSHP system construction. The evaluation results provide guidance for development planning of SSHP systems in Lanzhou New District and other regions with similar geological conditions.

Keywords: shallow geothermal energy; soil source heat pump; analytic hierarchy process (AHP); suitability; Lanzhou New District

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1 Geological Environment Background of the Study Area

1.1 Natural Geography Overview Lanzhou New District, approved by the State Council in August 2012, is the fifth national-level new district in China and the first in Northwest China. Located in the Qinwangchuan Basin to the north of Lanzhou' s main urban area, it lies between 36°26 40 -36°43 00 N and 103°33 00 -103°43 26 E, covering a planned total area of 1,744 km^2. By 2021, approximately 250 km^2 had been constructed with a permanent population of about 500,000. The study area comprises the built-up and core planning zones of Lanzhou New District, extending to Xiagushan in the north, Yujialiang in the south, Shanzi Dun in the east, and Xijia Chuan in the west, with an area of approximately 440.0 km^2.

Situated in the northwestern part of the Longxi Loess Plateau in the upper Yellow River basin, the region features a typical continental cold temperate semi-arid climate characterized by distinct seasons, abundant sunshine, cold dry winters, windy and rainless springs, hot humid summers, and cool autumns. The mean annual temperature is 6.9°C (at Zhongchuan Station), mean annual precipitation is 261 mm, mean annual evaporation is 1,879.8 mm, mean annual frost-free period is 139 days, mean annual sunshine duration is 2,659 hours, and maximum frozen soil depth is approximately 1.1 m. Prevailing winds are northwesterly in winter and spring, with an average annual wind speed of 2.3 m $\cdot$ s^{-1}. No perennial surface water exists within the territory; only a few gullies experience flood flows during summer and autumn rainstorms. The geomorphology can be classified into three types: denuded loess ridge-hill terrain, erosion-accumulation basins, and alluvial-proluvial gullies. Soil types mainly include irrigation silt soil, saline soil, meadow soil, gray-cinnamon soil, and black loam soil, supporting xerophytic and halophytic vegetation such as *Artemisia*, *Stipa*, *Agropyron*, and *Caragana* with coverage less than 30%.

1.2 Geological Environment Conditions Tectonically, the study area belongs to the Qinwangchuan erosion-accumulation basin on the eastern Qilian uplift belt of the Kunlun-Qinling geosynclinal fold system. The basin floor elevation ranges from 1,800 to 2,300 m. The surrounding mountains and hills are primarily composed of Neogene Miocene Xianshuihe Formation (N_1) sandstone-mudstone, mudstone intercalated with conglomerate, distributed in near-horizontal layers. Only a small amount of Silurian (S) sandstone, phyllite, and slate exists at the northeastern margin. Most surrounding hills are covered by Quaternary Upper Pleistocene Malan loess (Q_3). Within the basin, the upper strata are mainly Quaternary Middle-Upper Pleistocene ($Q_{2\ 3}$) sandy conglomerate, 20–40 m thick, locally calcareously cemented. The lower part consists of Neogene Miocene Xianshuihe Formation (N_1) sandy mudstone, mudstone intercalated with conglomerate, exceeding 200 m thick and forming the basin basement.

The upper loose rock layer locally hosts phreatic water with burial depth of 20-30 m, single-well yield of 20.3-70.6 $m^3 \cdot d^{-1}$, total dissolved solids (TDS) of 3–8 $g \cdot L^{-1}$ (maximum >10 $g \cdot L^{-1}$), and water chemistry dominated by $Cl \cdot SO_4$-$Na \cdot Mg$ type. The lower clastic rock layer contains confined water with aquifer roof depth of 200–800 m, single-well yield of 100–500 $m^3 \cdot d^{-1}$, TDS of 1–4 $g \cdot L^{-1}$, and water chemistry dominated by $SO_4 \cdot Cl$-Na and $Na \cdot Mg$ types. Due to deep groundwater burial, weak water richness, and poor water quality, the area shows poor suitability for groundwater source heat pump systems.

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2 Occurrence Conditions of Shallow Geothermal Energy

2.1 Stratigraphic Structure Within 200 m depth in the study area, strata are primarily Quaternary and Neogene. Quaternary thickness is 20–40 m above the constant temperature zone, which has limited significance for shallow geothermal energy occurrence. The underlying Neogene clastic rocks, with greater thickness and stable distribution, constitute the main occurrence zone for shallow geothermal energy resources. According to geological exploration data, the Neogene underlies the entire basin and its periphery, forming the Quaternary basement. Within the basin, the Miocene Xianshuihe Formation (N_1) consists of brownish-yellow, light orange-red, and rust-red sandy mudstone intercalated with sandy conglomerate in the middle-upper part, and gray-green conglomerate or sandstone at the base, with thickness exceeding 200 m. This upper Quaternary loose layer and lower Neogene clastic rock structure is widely distributed in semi-arid regions of central and eastern Gansu Province.

This stratigraphic pattern indicates that shallow formations in Lanzhou New District are dominated by Quaternary loose rocks and Neogene clastic rocks, particularly the latter with its extensive distribution and large thickness, providing favorable conditions for SSHP application. However, deep groundwater burial, weak water richness, and extremely uneven distribution severely limit suitability for groundwater source heat pump systems.

2.2 Thermophysical Parameters of Rock-Soil Mass

2.2.1 Parameter Definitions SSHP system performance is closely related to local rock-soil thermophysical properties. According to the *Technical Code for Ground Source Heat Pump Systems* (GB50366–2009), the following parameters primarily reflect rock-soil thermophysical performance effects on ground heat exchangers:

1. **Thermal conductivity (λ, $\mathbf{W \cdot m^{-1} \cdot K^{-1}}$)**: Influences rock-soil heat transfer performance, representing heat conducted per unit area per unit time under unit temperature difference. It reflects comprehensive heat transfer performance:

$$q_n = -\lambda \frac{\partial t}{\partial n}$$

   where q_n is heat flux in the heat transfer direction ($\mathrm{W \cdot m^{-2}}$), and $\frac{\partial t}{\partial n}$ is temperature gradient in the heat transfer direction ($\mathrm{K \cdot m^{-1}}$).

2. **Specific heat capacity (c, $\mathbf{J \cdot kg^{-1} \cdot K^{-1}}$)**: Heat absorbed or released per unit mass of rock-soil per temperature increase or decrease. As a multiphase material, specific heat capacity depends on the proportion and corresponding specific heat capacity of each component:

$$c = \frac{q}{m \cdot \Delta T}$$

   where q is heat absorbed or released by unit mass of rock-soil (J), m is mass (kg), and ΔT is temperature change value (K).

3. **Thermal diffusivity (α, $\mathbf{m^2 \cdot s^{-1}}$)**: Measures the rate at which temperature disturbance propagates from one point to another in rock-soil, reflecting temperature propagation speed:

$$\alpha = \frac{\lambda}{\rho c}$$

   where ρ is rock-soil density ($\mathrm{kg \cdot m^{-3}}$).

2.2.2 Thermophysical Parameters in the Study Area Through testing of rock cores from different strata within 200 m depth, Neogene clastic rock formations (mudstone, sandy mudstone, sandstone, sandy conglomerate) show thermophysical parameters (density, water content, thermal conductivity, specific heat capacity, thermal diffusivity) with average values higher than those of Quaternary loose formations (medium sand, silt, silty clay, angular gravel).

Since larger thermophysical parameters indicate higher thermal storage capacity, Neogene clastic rocks are more suitable for SSHP development than Quaternary loose formations.

Statistical analysis reveals that among Neogene clastic rock thermophysical parameters, thermal conductivity and thermal diffusivity show high consistency with density, while specific heat capacity shows high consistency with water content, with average correlation coefficients reaching 0.92 and 0.88, respectively. This demonstrates that the tested thermophysical parameters are reliable and have excellent application prospects.

2.3 Characteristics of Shallow Geothermal Field The Qinwangchuan Basin, where the study area is located, is a relatively tectonically stable zone with minimal crustal activity and weak internal Earth heat convection, resulting in relatively low terrestrial heat flow values averaging 64.99 $mW \cdot m^{-2}$. Within 200 m depth, ground temperatures show a consistent south-high, north-low planar distribution pattern: at 100 m depth, temperatures range 10.40–12.89°C; at 150 m depth, 12.18–15.20°C; and at 200 m depth, 13.54–17.95°C.

The constant temperature zone is located at 18-35 m depth with temperatures generally 9.82-11.60°C (average 10.70°C). Below the constant temperature zone to 200 m depth, geothermal gradient also shows south-high, north-low characteristics. The highest gradient areas are mainly distributed south of Luoquanwan-Zhongchuan Town, reaching 0.36–0.40$°C \cdot km^{-1}$; followed by central Zhongchuan Town area at 0.30–0.36$°C \cdot km^{-1}$; and large northern areas with gradients <0.30$°C \cdot km^{-1}$.

In summary, the study area features simple stratigraphy dominated by thick Neogene mudstone and sandstone formations with relatively high thermal conductivity, moderate specific heat capacity, and large thermal diffusivity coefficient. Combined with high shallow geothermal field temperatures and geothermal gradient, these conditions provide superior advantages for SSHP system development and utilization, forming the focus of this research.

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3 Mathematical Model for SSHP System Suitability Analysis

3.1 Evaluation Methods and Procedures The Analytic Hierarchy Process (AHP) is a systematic, hierarchical multi-objective decision analysis method that effectively combines measured data, expert scoring, and analysts' objective judgments. Its advantage lies in quantifying decision-makers' experiential judgments, proving more convenient when target factor structures are complex and necessary data are lacking. The procedure involves: (1) establishing an index evaluation system based on problem nature and target objectives (system target layer), organizing evaluation indicators and factors according to their attributes and subordination relationships; (2) comparing different evaluation indicators (element index layer) at the same level (attribute criterion layer) to quantify their relative importance and construct judgment matrices; (3) calculating relative importance order values (weights) for each indicator in the element index layer from the judgment matrices and performing consistency tests; and (4) determining comprehensive evaluation results of element index layer factors on the system target layer based on the established mathematical evaluation model.

3.2 Establishing the Evaluation Index System Rational determination of an SSHP system evaluation index system forms the foundation for correct suitability assessment. Based on characteristics of influencing factors for SSHP systems in Lanzhou New District and analysis of existing domestic research results, we established an SSHP system suitability evaluation system for Lanzhou New District [Figure 4: see original paper]. The system comprises three hierarchical levels: Level 1 is the system target layer—SSHP suitability evaluation system (X); Level 2 is the attribute criterion layer—hydrogeological conditions (X_1), geothermal field characteristics (X_2), and rock-soil mass thermophysical properties (X_3); Level 3 is the element index layer—groundwater burial depth (X_{11}), aquifer thickness (X_{12}), groundwater flow velocity (X_{13}), geothermal gradient (X_{21}), initial average ground temperature (X_{22}), average thermal conductivity (X_{31}), and average specific heat capacity (X_{32}).

3.3 Determining Judgment Matrices at Each Level In the hierarchical structure, factors at the same level subordinate to (or influencing) each upper-level factor are pairwise compared regarding their importance to the criterion, quantified according to a predetermined scale to construct judgment matrices. Matrix element values are determined by multiple experienced technical professionals collectively assessing relative importance. Given shortcomings of the traditional "1-9 scale method," this study adopts the index scale method to construct attribute criterion layer and element index layer judgment matrices.

3.4 Determining Factor Weights and Consistency Test Based on judgment matrices, we precisely calculate the eigenvector corresponding to the maximum eigenvalue. This eigenvector represents the importance ranking of evaluation factors, which after normalization becomes the ranking weight of relative importance of same-level factors to upper-level factors. To verify rationality of the eigenvector derived from judgment matrices, consistency tests are required using the following formulas:

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

$$CR = \frac{CI}{RI}$$

where CR is consistency ratio; CI is consistency indicator; $\lambda_{\max}$ is maximum eigenvalue of judgment matrix; n is number of elements in judgment matrix;

and RI is average random consistency indicator . When $CR < 0.1$, judgment matrix consistency is considered satisfactory; otherwise, the matrix requires revision. Smaller CR values indicate higher consistency and more reasonable mathematical evaluation models.

Thus, we ultimately determined weights of element index layer factors to attribute criterion layer and system target layer, passing consistency tests . Results show that consistency test results for element index layer weights in the study area' s SSHP system are $CR = 0.0032$ and $CR = 0.0081$, indicating high credibility of the established hierarchical weight values for Lanzhou New District.

3.5 Establishing the Evaluation Mathematical Model 1) SSHP System Suitability Evaluation Model

Based on the constructed evaluation system, selected element indicators, and determined weights, the SSHP system suitability evaluation model using the comprehensive index method is:

$$B = \sum_{j=1}^{n} W_j Y_j \quad (j = 1, 2, \dots, n)$$

where B is the SSHP system suitability evaluation comprehensive index; W_j is the weight of the jth element indicator factor in the target layer ($W_j = \sum_{i=1}^{3} W_{ij}$); Y_j is the assigned value of the jth index layer influencing factor; and n is the number of indicator elements in the SSHP system suitability evaluation system.

2) Dimensionless Processing of Index Layer Factors

Since index layer factors have different dimensions and widely varying magnitudes, dimensionless processing is required for calculation and analysis convenience:

$$Y_{ijw} = \frac{X_{ij} - X_{\min}}{X_{\max} - X_{\min}}$$

where Y_{ijw} is the processed value of index layer factors; X_{ij} is the measured value; $X_{\max} = \max[X_{ij}]$; and $X_{\min} = \min[X_{ij}]$.

3) Element Indicator Zoning and Assignment

Research shows that long-term effective SSHP application depends on the seven element indicators listed above. Since these indicators have different value ranges and non-uniform linear variation across the area—some spanning several orders of magnitude (e.g., groundwater burial depth, flow velocity)—and not all are positive-effect indicators (e.g., groundwater burial depth is a negative-effect indicator), simple dimensionless processing cannot accurately express the true relationship between values and SSHP suitability. Therefore, we optimized the dimensionless method by collecting existing SSHP system development case parameters from the study area and similar geological regions in the province, analyzing threshold values suitable for SSHP development, and assigning values based on these thresholds. Higher assigned values Y_j indicate greater suitability for SSHP application. We classified indicators as very favorable ($Y_j = 10$), favorable ($Y_j = 8$), moderately favorable ($Y_j = 6$), less favorable ($Y_j = 4$), and unfavorable ($Y_j = 2$) .

4) SSHP System Suitability Zoning Standards

Based on calculated suitability evaluation index (B) results, combined with operational SSHP projects in Lanzhou New District and Lanzhou City, and referencing suitability zoning standards from developed regions like Beijing and Tianjin, we classified SSHP system suitability in Lanzhou New District as: suitable ($B > 7.0$), relatively suitable ($5.0 < B \leq 7.0$), and unsuitable ($B \leq 5.0$).

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4 SSHP System Suitability Evaluation Results

4.1 Suitability Zoning in Lanzhou New District Data sources for this evaluation include: geological data (latest 1:200,000 regional geological maps and descriptions); hydrogeological data (1:50,000 regional water supply hydrogeological maps, latest reports and test data from groundwater and geological environment exploration/evaluation, and regional hydrogeological surveys); and shallow geothermal energy data (recent investigation and evaluation reports from the area). All data passed expert review, and further screening ensured authenticity, accuracy, and representativeness.

The evaluation shows that suitable SSHP zones cover 249.52 km^2 (56.71% of study area) with B values of 7.0007–8.9543; relatively suitable zones cover 109.94 km^2 (24.99%) with B values of 5.0023–6.9981; and unsuitable zones cover 80.54 km^2 (18.30%) with B values of 2.5487–4.9695. Combined suitable and relatively suitable areas total 359.46 km^2, accounting for 81.70% of the study area [Figure 5: see original paper].

4.2 Suitability Evaluation Analysis **Suitable zones** are mainly distributed in the basin plain area south of Laijiapo-Luoquanwan line and north of Zengjiazhuang-Shigoumen line. The upper Quaternary layer is generally 20–40 m thick, underlain by interbedded Neogene mudstone and sandstone. Aquifer thickness is 10–30 m, groundwater flow velocity 0.2–0.5 m·d^{-1}, geothermal gradient 0.35–0.50°C·km^{-1}, average specific heat capacity 0.92–1.04 kJ·kg^{-1}·K^{-1}, initial average ground temperature 14.0–16.0°C, and average thermal conductivity 3.2–3.8 W·m^{-1}·K^{-1}.

Relatively suitable zones are distributed in the plain area between Shanghuajiajing and Qinchuan Town in the north-central basin. The upper Quaternary conglomerate is about 10–30 m thick, underlain by Neogene mudstone and sandstone. Aquifer thickness is 10–30 m, groundwater flow velocity 0.1-0.2 $m \cdot d^{-1}$, geothermal gradient 0.30–0.40°$C \cdot km^{-1}$, initial average ground temperature 13.0–14.5°C, average thermal conductivity 2.4-3.2 $W \cdot m^{-1} \cdot K^{-1}$, and average specific heat capacity 0.88-0.92 $kJ \cdot kg^{-1} \cdot K^{-1}$.

Unsuitable zones are distributed in loess hills and bedrock mountains on both sides of Qinwangchuan Basin, covered by 15–30 m thick Quaternary eolian deposits that are essentially water-free, underlain by Neogene clastic rocks and minor Silurian metamorphic rocks. These areas have low rock-soil thermophysical parameters and geothermal temperatures, with some zones developing geological hazards such as collapses and loess collapsibility, making them unsuitable for shallow geothermal energy development.

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5 Discussion

The improved AHP method yields evaluation results that closely match regional hydrogeological conditions, geothermal field characteristics, and rock-soil thermophysical properties in Lanzhou New District, overcoming one-sided influences of subjective factors. This demonstrates that the selected evaluation method is rational, with comprehensive evaluation factors and a scientifically sound mathematical model. The evaluation results provide important guidance for SSHP system construction and development planning in Lanzhou New District.

Key improvements include: (1) Adopting index scale method instead of traditional 1–9 scale, which better avoids judgment matrix distortion and accelerates consistency testing, showing good feasibility and scientific validity; (2) Optimizing element indicator assignment by using statistical analysis of existing application cases from adjacent and similar regions rather than simple dimensionless processing, making assignments more realistic and evaluation results more accurate and credible; (3) The established evaluation system encompasses all major factors affecting SSHP suitability, reflecting both logical relationships between influence factors and evaluation indicators, and demonstrating importance and comprehensiveness of element indicators in the evaluation process.

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6 Conclusions

Based on systematic analysis of shallow geothermal energy occurrence conditions in Lanzhou New District and application of improved AHP for SSHP system suitability evaluation, we draw the following conclusions:

1. **Lanzhou New District**, located in a cold temperate semi-arid climate zone of northwestern China with relatively scarce groundwater resources,

is unsuitable for groundwater source heat pump systems. However, its superior geological structure, rock-soil thermophysical properties, and geothermal field conditions provide favorable conditions for large-scale SSHP application.

2. **Weight calculations** through AHP reveal that average thermal conductivity and geothermal gradient are the most influential factors affecting SSHP suitability. Evaluation results show that suitable and relatively suitable zones cover 359.46 km^2 (81.07% of study area), mainly distributed in the extensive Qinwangchuan Basin plain area. Other areas have low rock-soil thermophysical parameters and geothermal temperatures, with some developing shallow geological hazards, making them unsuitable for shallow geothermal energy development.

3. **The improved AHP** yields evaluation results highly consistent with actual hydrogeological and geothermal conditions, overcoming subjective bias. This confirms the rationality of the selected evaluation method, comprehensive factors, and scientifically robust mathematical model. The evaluation results provide important guidance for SSHP system planning and development in Lanzhou New District and similar regions in northwest China’ s arid climate zones.

References: (Preserved as in original manuscript)

Note: Figure translations are in progress. See original paper for figures.