S1 Evaluation index system of new rural integrated energy system

The evaluation index system of novel rural integrated energy system is considered from seven aspects: energy efficiency, energy supply, low-carbon sustainability, environmental impact, energy economy, social benefits, and integrated energy system development.

S1.1 Energy Efficiency

1) Integrated Energy Utilization Rate comprehensively reflects the overall energy efficiency in rural areas, covering production, conversion, transmission, and end-use processes.

Definition: Ratio of system output energy to input energy, reflecting energy utilization efficiency.

$$\text{Integrated Energy Utilization Rate} = \frac{\text{Electrical efficiency}\times\text{electrical load}}{\text{total load}} + \frac{\text{Thermal efficiency}\times\text{Thermal load}}{\text{total load}} + \frac{\text{Gas efficiency}\times\text{gas load}}{\text{total load}}$$

Electrical efficiency = electrical load/total input energy

Thermal efficiency = Thermal load/total input energy

Gas efficiency = gas load/total input energy

2) Renewable Energy Consumption Rate directly reflects the degree of utilization of renewable energy in rural areas. Because renewable energy is usually consumed on the spot, it also reflects the dependence of the integrated energy system on external energy supply.ortion of total energy actually used from renewable energy sources in a given period of time in an area.

Renewable Energy Consumption Rate

=Wind energy consumption rate+Solar consumption rate+Biomass consumption rate+Geothermal consumption energy

Wind energy consumption rate = act

Definition: A measure of the propual wind power generation/total load

Solar consumption rate = (actual solar power generation + solar heat production)/total load

Biomass consumption rate = (biomass power generation + biomass gas energy)/total load

Geothermal consumption energy = (geothermal power generation + geothermal heat generation)/total load

3) System exergy efficiency takes into account the change of energy quality and can truly reflect the effective utilization of energy in the process of conversion and utilization. Compared with traditional energy efficiency, exergy efficiency not only considers the amount of energy, but also the quality and availability of energy, which makes the evaluation more accurate and comprehensive.

Definition: exergy utilization efficiency of a system's exergic energy obtained from the environment in the process of energy conversion and utilization.

Since the system is too large, exergy efficiency can be mainly considered in the following production scenarios.

$$\text{System Exergy Efficiency} = \frac{\text{electrical load}+\text{thermal load}\left(1-\frac{T_0}{T_{th}}\right)+\text{gas chemical exergy}\times\text{gas load}}{\varepsilon_{PV}+\varepsilon_{wind}+\varepsilon_{geo}+\varepsilon_{CHP}+\varepsilon_{solar}+\varepsilon_{bio}+\varepsilon_{tur}} \quad \text{(S1)}$$

T_0 is the average ambient temperature (K); T_{th} is the temperature for supplying hot water or steam (K). Gas chemical exergy is approximately equal to 1.05 times the gas calorific value.

PV exergy efficiency:

$$\varepsilon_{PV}=W/(I\cdot A\cdot(1-T_0/T_s) \tag{S2}$$

W is the photovoltaic output power (kW); I is the average solar radiation intensity (kW/m²); A is the surface area of the photovoltaic panel (m²); T_0 is the average ambient temperature (K); T_s is the sun's surface temperature (K).

Wind turbine exergy efficiency:

$$m=\rho\times A\times V_i \tag{S3}$$

$$\varepsilon_{wind}=W/(m\cdot exi) \tag{S4}$$

m is the air quality flow rate (kg/s); ρ is the average air density (kg/m³); A is the average wind turbine area (m²); V_i is the average air velocity (m/s); exi is the fan inlet enthalpy; W is the rated power of the wind turbine (kW).

Geothermal exergy efficiency:

$$\varepsilon_{geo}=(W+Q)/(m[(h_i-h_o)-T_s(s_i-s_o)]) \tag{S5}$$

m is the mass flow rate of geothermal fluid (kg/s); h_i is the enthalpy of heat flow fluid outlet; h_o is the heat flow fluid inlet enthalpy; T_s is the average temperature of heat flow fluid; s_i is the outlet entropy of heat flow fluid; s_o is the outlet entropy of heat flow fluid; Q is the geothermal heat production power (kW); W is the output power of electric energy (kW).

Biomass direct combustion exergy efficiency:

$$\varepsilon_{CHP}=W/(m\times LHV) \tag{S6}$$

m is the biomass mass flow rate (kg/s); LHV is the low heating value of fuel (kJ/kg); W is the output power of electric energy (kW).

Solar thermal exergy efficiency:

$$\varepsilon_{solar}=[m\times((h_o-h_i)-T_h\times(s_o-s_i))]/[I\times A\times(1-T_o/T_s)] \tag{S7}$$

m is the mass flow rate of hot water (kg/s); h_i is the enthalpy of hot water outlet; h_o is the enthalpy of hot water inlet; s_i is the hot water outlet entropy; s_o is hot water outlet entropy; T_h is the average water temperature of the collector（K）； I is the average solar radiation intensity (kW/m²); A is the surface area of the solar collector (m²); T_o is the average ambient temperature (K); T_s is the sun's surface temperature (K).

Biomass gasification exergy efficiency:

$$\varepsilon_{bio}=m_o\times LHV_o/(m_i\times LHV_i) \tag{S8}$$

m_i is the mass flow rate of imported biomass (kg/s); LHV_i is the low heating value of imported biomass (kJ/kg); m_o is the mass flow rate of exported biomass (kg/s); LHV_o is the low heating value of exported biomass (kJ/kg)

Gas turbine exergy efficiency:

$$\varepsilon_{tur}=W/(m\times LHV) \tag{S9}$$

m is the mass flow rate of imported gas (kg/s); LHV is the low heating value of gas (kJ/kg); W is the output power of electric energy (kW).

4) Equipment Utilization Rate reflects the degree of utilization and efficiency of energy equipment. It can reflect whether the configuration of energy equipment is reasonable. The higher Equipment Utilization Rate enables the system to operate in an efficient and reasonable state, reduce energy waste and improve the overall energy utilization efficiency.

Definition: The proportion of the actual use time or production output of the equipment in a certain period of time to its theoretical available time or maximum capacity.

$$\text{Equipment Utilization Rate}=\sum \text{all Equipment Utilization Rate}/\text{quantity}$$

Equipment Utilization Rate=actual output power/rated output power

5) Biomass Energy Output Ratio reflects the efficiency of non-electric utilization of biomass, regardless of additional consumption such as electric energy. This ratio is used to measure the energy efficiency level of biomass energy. A higher value indicates a greater energy output of biomass energy relative to the input energy, thereby signifying higher energy efficiency.

Definition: The ratio between the available energy produced in the conversion process of biomass energy and the energy consumed in its production.

Biomass Energy Output Ratio = unit product energy output/energy input per unit of product

S1.2 Energy Supply

1) User Satisfaction is obtained through user research, which directly reflects rural users' feelings on the use of energy services. High satisfaction indicates that energy services can effectively meet the needs of residents, scored 0–100.

Definition: User Satisfaction refers to the degree of match between the user's expectation of the product or service and the actual experience. It reflects whether the user's satisfaction with the product or service has reached their expected level.

2) Power Sales Loss is used to assess the gains and losses of the power grid in the process of purchasing electricity when the power supply of the integrated energy grid is insufficient. It reflects whether the integrated energy system can fully meet the load demand.

Definition: The profit or loss resulting from the purchase of electricity from the grid.

$$G=Q\times(Po-C_g) \tag{S10}$$

G is the profit and loss of power grid sales (CNY 10,000); Q is the annual electricity purchased by the user (kWh); Po is the average retail price of the power grid (yuan /kWh); C_g is the average cost of electricity sold on the grid (yuan /kWh).

3)End-user Energy Quality directly reflects the energy supply quality of the energy system. High quality energy supply can meet the needs of users and improve users' satisfaction with energy services.

Definition: The degree of quality of energy obtained by the user in the process of energy use. The Total Harmonic Distortion (THD) and Voltage Compliance Rate are used to reflect the power quality, the Exergy Quality Factor reflects the heat energy quality, and the Gas Calorific Value reflects the gas supply quality.

The Total Harmonic Distortion (THD) is expressed as the percentage ratio of the root mean square (RMS) value of all harmonic components to the RMS value of the fundamental component in a periodic non-sinusoidal signal. V_1: RMS value of the fundamental component (frequency f1); V_n: RMS value of the n-th harmonic component (frequency n×f1).

$$\mathrm{THD}=\frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1}\times 100\% \tag{S11}$$

Exergy Quality Factor=1- cold source temperature/heat source temperature

The Voltage Compliance Rate is the ratio of the total time of the grid monitoring point voltage within the qualified range and the total monitoring time of the period within the statistical period. See the Exergy Quality Factor in GB/T12325 "Power quality Supply Voltage Deviation" for details. The Gas Calorific Value refers to the amount of heat released per unit volume or unit mass of gas during complete combustion.

4) Supply Reliability reflects the continuity and stability of energy supply. Renewable energy sources (such as solar, wind, biomass, etc.) are usually intermittent and volatile. The integration and utilization of renewable energy in the energy system is enhanced by improving and optimizing energy management and energy storage technologies. The rural economy and agricultural production have a great dependence on a stable energy supply, and a reliable energy supply can ensure the normal operation of agricultural irrigation, mechanized operations, agricultural product processing and other activities.

Definition: The ability of energy to be continuously supplied to users under specified conditions and for a specified period of time according to predetermined requirements.

Power Supply Reliability Rate:

$$C=\left(1-\frac{\Sigma t_m}{T\times M}\right)\times 100\% \tag{S12}$$

t_m is the total power outage time of the m-th billing user (h); M is the total number of billing users in the distribution network; T is the statistical time (h).

Thermal Loss Rate of Pipe Network:

$$\mu=\frac{YRD_r}{Z_r} \tag{S13}$$

Y is the length (m) of the hot water transmission pipeline; R is the heat loss per unit pipe length (kW/m); Dr is the actual heating time (h); Zr is the amount of hot water pipe heating (kWh).

Gas Supply Reliability:

$$R=\frac{V_X}{V_D} \tag{S14}$$

Where, refers to the supply gas volume (m^3) of the pipe network and the demand gas volume (m^3).

S1.3 Low-carbon Sustainability

1) GHG Emissions

Definition: GHG Emissions from a system are analyzed using the Life Cycle Assessment (LCA). These gases mainly include CO_2, CH_4, N_2O and other gases that have a greenhouse effect on the Earth's atmosphere.

2) SO_x Emissions

Definition: The total amount of sulfur oxides (mainly SO_2 and SO_3) emitted into the atmosphere.

3) NO_x Emissions

Definition: The total amount of nitrogen oxides such as (NO) and (NO_2) emitted into the atmosphere by the system.

4) Particulate Matter (PM) Emissions

Definition: The total amount of solid or liquid particles released into the atmosphere.

Emissions = Emission Factors * energy supply quantity

For Emission factors, see "China Product Life Cycle GHG emission Factor Database", "Manual of Accounting Methods and Coefficients for Emissions from Statistical Survey of Emission Sources".

S1.4 Environmental Impact

Full compliance with the requirements of relevant standards will be scored 10/10, while complete non-compliance will receive a score of 0 points.

1) Noise Environmental impact: It should comply with "Environmental Impact Assessment Technical Guidelines for Acoustic Environment" (HJ 2.4), "Urban Area Environmental Noise Application Area Division" (GB/T19190), "Industrial Enterprise Factory Boundary Noise Standard" (GB 12348) and other relevant standards.

Definition: refers to the adverse effects of sound from various sources on human health, quality of life and ecosystem.

2) Electromagnetic Environmental Impact: It should comply with "Relevant Provisions of the Electromagnetic Environment Control Limit" (GB 8702), "Environmental Electromagnetic Wave Health Standard" (GB 9175), "Urban Distribution Network Planning and Design Code" (GB 50613) and other relevant standards.

Definition: The potential effects and risks of electromagnetic fields (such as radio spectrum, electromagnetic radiation, etc.) on human health, electronic equipment, communication systems and ecosystems.

3) Atmospheric Environmental Impact: It should meet "Relevant Provisions of Environmental Quality Standards" (GB 3095), "Battery Industry Pollutant Emission Standards" (GB 30484), "Thermal Power Plant Atmospheric Pollutant Emission Standards" (GB 13223) and other relevant standards.

Definition: The negative effects of atmospheric pollutants (e.g. PM, SO_2 , NO_x, etc.) on human health, ecosystems, and climate.

4)Water Environmental Impact: It should meet "Relevant Provisions of Groundwater Quality Standards (GB/T 14848) and Surface Water Environmental Quality standards" (GB 3838) and other relevant standards.

Definition: The adverse impact of various factors (such as industrial wastewater, agricultural discharge, urban sewage, etc.) on the quality of water bodies and ecosystems, including water quality pollution, biodiversity reduction, water resources reduction and other issues.

5) Ecological Environmental Impact: It should meet the relevant provisions of relevant standards such as "Ecological Impact

in the Technical Guidelines for Environmental Impact Assessment (HJ 19)".

Definition: Changes and damage caused by human activities to natural ecosystems and their components (including species, habitats and ecological processes).

Complete compliance is rated on a scale of 10, while complete non-compliance is rated on a scale of 0.

S1.5 Energy Economy

1) Life Cycle Cost (LCC) includes everything from the design, construction, operation, maintenance and final disposal of the energy system. Through the Life Cycle Analysis, the economic benefits of energy projects can be comprehensively evaluated, not only the initial investment cost, so as to make more scientific and rational investment decisions. It includes the initial investment cost, operation and maintenance cost, and residual value of fixed assets.

Life Cycle Cost=initial investment cost + operation and maintenance cost-residual value of fixed assets

2) Return on Investment (ROI) can directly understand the profitability of the project to ensure that the resource investment can obtain the expected economic return. In the case of limited resources, choosing a project with a high ROI can ensure the efficient use of resources, optimize the allocation of resources, and improve the overall economic benefits.

Definition: The ratio of the profit obtained from an investment to the cost of the investment.

EBIT is the average annual pre-tax profit during the operating period, and TI is the total investment of the project.

$$\mathrm{ROI}=\frac{\mathrm{EBIT}}{\mathrm{TI}}\times 100\% \tag{S15}$$

3) Payback Period is an important index to evaluate investment risk. A shorter payback period means that the project can recover its initial investment more quickly, reducing the risk of capital recovery and increasing the attractiveness and security of the investment. In rural areas, where funds are usually more limited, the Payback Period can help evaluate the efficiency of capital utilization in different energy projects. By choosing projects with a shorter payback period, the reuse of funds can be realized more quickly, supporting more project implementation and development.

Definition: The length of time an investment project takes from the time it begins to invest money to the time it recoups its full investment costs and begins to make a profit.

$$\sum_{t=0}^{y}(C_I-C_O)_t=0 \tag{S16}$$

C_I is the cash inflow (CNY 10,000); C_O is the cash outflow (CNY); y is the payback period.

4) Levelized Cost of Energy (LCOE) includes all kinds of expenses in the life cycle from energy production, conversion, transmission to final use, and considers all aspects of the energy project more comprehensively. A lower LCOE means that the project has a higher economic efficiency.

Definition: The combined cost required to produce or provide each unit of energy, such as per kilowatt-hour of electricity, per cubic meter of natural gas, or per ton of coal.

$$LCOE=\frac{I_0-\frac{V_R}{(1+i)^N}+\sum_{n=1}^{N}\frac{A_n+D_n+P_n}{(1+i)^n}}{\sum_{n=1}^{N} Y_n}\times 10000 \tag{S17}$$

LCOE is the unit energy cost (CNY/kWh); I_0 is the initial investment (CNY 10,000); V_R is the salvage value of fixed assets (CNY 10,000); N is the project operating life (years); A_n is the operation cost in the n-th year (CNY 10,000); D_n is the depreciation for the nth year (CNY 10,000); P_n is the interest for the nth year (CNY 10,000); Y_n is the Energy supply quantity for the n-th year (kWh); I is the discount rate.

5) Energy Intensity is usually used to assess the efficiency of energy use in economic activities of a country or region and the degree of energy dependence of the economy. A lower Energy Intensity means that less energy is consumed in economic activities, indicating higher energy utilization efficiency and lower energy consumption costs.

Definition: The amount of energy consumed per unit of Gross National Product (GDP) or unit of produced output.

$$c_0=\frac{C}{GDP} \tag{S18}$$

c_0 is the energy consumption per unit of GDP (GWh/ CNY 100 million); C is the total energy consumption (GWh); Regional GDP (billion yuan)

S1.6 Social Benefits

1) Employment Benefits are directly related to the economic development of rural areas. By increasing employment opportunities, residents' income can be increased, their spending power enhanced, and the overall development and prosperity of the local economy promoted. Energy projects with high Employment Benefits are usually more sustainable. Through job creation, coordinated economic, social and environmental development can be achieved to promote sustainable development in rural areas.

Employment Benefits = number of jobs provided/total local population

2) Poverty Alleviation Benefits mean that the quality of life of residents in rural areas can be significantly improved by improving infrastructure and providing stable energy supply. Or drive the development of related industries, and further promote the overall economic improvement of poor areas. By creating jobs, we can help the poor people get rid of poverty, alleviate the poverty phenomenon and achieve stable poverty alleviation effects.

Poverty Alleviation Benefits = contribution to local GDP/local GDP

3) Industrial Benefits refer to the fact that energy projects can provide stable and reliable energy supply to rural areas and support the development of local agriculture, industry and services. Through the implementation of energy projects, the rise of emerging industries and the upgrading of traditional industries can be promoted, and industrial diversification and economic structure optimization can be promoted. Energy projects can drive the development of upstream and downstream industries, improve the industrial chain, and form an industrial cluster effect.

Industrial Benefits = the quantity of newly emerging industries/total number of industries

4) Public Green Mobility Rate can reflect the popularity of public transportation and green travel, and formulate more reasonable transportation planning and policy measures to reduce the dependence on fuel vehicles, which can reduce the demand

for fossil fuels, promote the optimization of energy structure and reduce the dependence on non-renewable resources such as oil, contribute to environmental protection and sustainable development of rural areas.

Definition: The proportion of residents using electric vehicles for their travel.

Public Green Mobility Rate = electric vehicles/total number of vehicles

5)Electric Vehicle Charging Coverage can measure the popularity and placement of charging infrastructure in a region. The improvement of charging infrastructure can eliminate potential users' concerns about the convenience of charging, increase the purchase and utilization rate of electric vehicles, and promote the electrification of transportation. The improvement of charging pile coverage requires a lot of infrastructure construction, including the expansion and upgrading of the power network.

Definition: The ratio of the service range of charging piles in a certain area to the demand range of the area.

Electric Vehicle Charging Coverage = charging pile service radius * Number of charging piles/total demand area

S1.7 Integrated Energy System Development

1) Energy Storage Configuration Ratio can reflect the reasonable degree of energy storage equipment Settings. The energy storage system can store excess energy when there is an imbalance between energy supply and demand, and release it when demand peaks, thereby improving the overall energy utilization efficiency. Energy storage systems can balance out fluctuations in energy supply, especially in situations where renewable energy generation, such as solar and wind, is intermittent and unstable. A higher Energy Storage Configuration Ratio can ensure the stability and reliability of energy supply in rural areas.

Definition: The ratio of the total capacity of all energy storage devices in the system to the total capacity of all devices in the system.

$$\eta_{se}=\frac{\sum_{n=1}^{N} W_{ac}^{n}}{\sum_{s=1}^{S} W_{ec}^{s}} \tag{S19}$$

W^{n}_{ac} refers to the capacity of the energy storage equipment of the corresponding energy type; W^{s}_{ec} is the capacity of the S-th device in the system.

2)Decentralization Index can reflect the degree of dispersion of new energy access in the distributed network .A higher Decentralization Index indicates a more even distribution of new energy across each access point, which is conducive to the local consumption of new energy and reduce the impact on the power grid. A balanced distribution of energy resources can improve the reliability of energy supply.

$$C_D=1-\max\left(\left|\frac{P_{N,i}-P_{avg}}{P_{avg}}\right|\right)\times 100\% \tag{S20}$$

P_{avg} is the average rated power of new energy of all access points in the distribution network; $P_{N,i}$ is the rated power of the i-th new energy source.

3) Power Grid Upgrade and Expansion Delay is used to evaluate the impact of energy storage equipment in the integrated energy system on power grid upgrade and expansion.

By calculating the peaking effect of energy storage equipment during peak load hours, the upgrade and expansion demand of the power grid can be delayed.

$$\Delta N=\frac{\log\frac{1}{(1-\alpha)}}{\log(1+\tau)} \tag{S21}$$

ΔN is the delay time of power grid expansion; α is the peak cutting coefficient of energy storage equipment; τ is the annual load growth rate.

4) Rural Electrification Rate refers to the construction of power infrastructure and the popularization of power services in rural areas. To a certain extent, it reflects the development of agricultural mechanization, rural industrialization and service industry in rural areas.

Rural Electrification Rate = total electricity consumption/number of users

5)Energy Self-consumption Rate refers to the proportion of the energy produced by the system in a given period that is consumed by the system itself. It reflects the degree of self-sufficiency in the production and use of energy.

Energy Self-consumption Rate =1- (annual purchased electricity + annual purchased gas)/total energy supply quantity

6) Energy Consumption per 10,000 CNY Output reflects the energy consumption required per unit of economic output. It is generally used to measure the completion of the comprehensive smart energy plan of provinces and cities or regions

Energy Consumption per 10,000 CNY Output = total energy consumption *10000/ total gross output value

Total energy consumption refers to all energy consumed in a year (kWh); total Gross output refers to the total economic output created in the same period (ten thousand CNY).

S2

S2.1

Table S1 Random consistency index *RI*.

Rank	3	4	5	6	7	8	9	10
RI	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49

Table S2 The mapping relationship between r_{ij} and r^*_{ij}.

r_{ij}	r^*_{ij}	r_{ij}	r^*_{ij}
1/9	0.1	2	0.55
1/8	0.15	3	0.6
1/7	0.2	4	0.65
1/6	0.25	5	0.7
1/5	0.3	6	0.75
1/4	0.35	7	0.8
1/3	0.4	8	0.85
1/2	0.45	9	0.9

1	0.5

S2.2

Table S3 Data of Evaluation Indicators for the Three Pilot Counties

Indicator	Wendeng District, Shandong Province	Changfeng County, Anhui Province	Liyang City, Jiangsu Province
Integrated Energy Utilization Rate (%)	28.6	31	35
Renewable Energy Consumption Rate (%)	60.26	50.6	62.47
System Exergy Efficiency (%)	28.59	30.2	34.8
Equipment Utilization Rate (%)	20.7	57.36	58
Biomass Energy Output Ratio	2.7	3.1	3.2
User Satisfaction (score)	82	87.3	89
Power Sales Loss (10,000 CNY)	7.6635	19.55	11
End-user Energy Quality			
Total Harmonic Distortion (%)	4.37	3.66	5.32
Voltage Compliance Rate (%)	99.945	99.98	99.98
Exergy Quality Factor	0.124	0.132	0.118
Gas Calorific Value (MJ/m3)	16	22	21
Supply Reliability			
Power Supply Reliability Rate (%)	99.9816	99.99	99.95
Thermal Loss Rate of Pipe Network (%)	9.13	7.98	7.42
Gas Supply Reliability (%)	83	85.32	88.1
GHG Emissions (10,000 t)	852	746	826
SOx Emissions (t)	3482	1136	1572
NOx Emissions (t)	9434	8362	4068
Particulate Matter Emissions (t)	5691	1828	2237
Noise Environmental Impact (score)	6	6	7
Electromagnetic Environmental Impact (score)	8	6	8
Atmospheric Environmental Impact (score)	8	8	8
Water Environmental Impact (score)	7	9	7
Ecological Environmental Impact (score)	8	8	9
Life Cycle Cost (100 million CNY)	165	101.62	176.5
Return on Investment (%)	10.33	6.88	9
Payback Period (year)	9.6	14.5	9.8
Levelized Cost of Energy (CNY/kWh)	0.35	0.305	0.41

Energy Intensity (GWh/100 million CNY)	4.91	27.676	0.7816
Employment Benefits	1.6	0.8	0.2
Poverty Alleviation Benefits	7.2	9	8.6
Industrial Benefits	2.6	3	3.6
Public Green Mobility Rate (%)	77	63	59.38
Electric Vehicle Charging Coverage (%)	20	9	6.4
Energy Storage Configuration Ratio (%)	32.7	33	13
Decentralization Index (%)	23	31	35
Power Grid Upgrade and Expansion Delay (year)	15.4	15.6	14.8
Rural Electrification Rate (%)	94.6	90	92
Energy Self-consumption Rate (%)	72	68	64
Energy Consumption per 10,000 CNY Output (kWh/10,000 CNY)	491	276.76	78.16