Optimal design of distributed energy systems in rural area of developing country: a case study of Guanzhong area, China

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Abstract: This paper optimized the design of renewable distributed energy systems (R-DES) based on interval linear programming. The total cost of this system is used as an objective function of system configuration problem. The optimal configuration of this system is obtained. In order to prove practicability of this system, this paper took the remote rural areas of Guanzhong as an example to optimize energy supply and operation mode. Through calculations, it can be seen that this system reduced power supply by 29.0%~63.6%, and carbon emission reduction rate is 4.0%~49.6%.

Keywords: optimal design; distributed energy systems; rural area; uncertainty

1. Introduction
In 2017, the Ministry of Housing report that China's rural residential area reached 32.32 billion m², which higher 23.3% than 2012. The building industry is considered to be a major contributor to the world's energy consumption. During construction and operation, the energy consumption of buildings accounts for 40%. Among construction energy consumption, rural residential buildings consume 60% in China[1]. However, with the rapid development of country’s economy and the improvement of residents on living standards, comfortable quality of buildings in rural area is increasing, which leads to the increase of construction energy consumption rapidly.

In this study, the optimization of R-DES using interval linear programming (ILP) was researched to coordinate the relationship between energy supply, economic benefits and environmental protection. ILP is used to deal with uncertainties resulting from the range of admissible values in problem coefficients[2]. R-DES has some advantages: a) Ability to meet the needs of special areas for energy. For instance, rural, pastoral, mountainous and developing areas; b) Improve the reliability and stability of energy supply; c) Provide the potential for the use of cascade energy[3]; d) Realize the comprehensive utilization of various renewable energy sources[4].

2. Application
2.1 Overview of the study area
The research area is Guanzhong area. According to the “Development Plan of Guanzhong Plain Urban Agglomeration” published by National Development and Reform Commission Ministry of Housing and Urban-Rural Development in 2018, Guanzhong Plain Urban Agglomeration refers to the center of Xi’an (including Xianyang) and Baoji as sub-centers, including Weinan, Tongchuan, Shangluo and Yangling. Demonstration area city group, Pingliang, Qingyang, Linyi, Yuncheng[5]. In the urban area, the land area is 107,100 km². By the end of 2017, the permanent population was 38.65 million, and the regional
GDP was 216 billion RMB. The Guanzhong Plain Urban Agglomeration locates in a cold temperate zone with an average elevation of about 500 m. The climate is characterized by four distinct seasons: hot summer, cold winter, great temperature difference. The rural areas in Guanzhong are underdeveloped and the living conditions of the residents are relatively backward. Especially, the indoor thermal environment is poor in winter. Residents use coal or electric heating, which not only consumes a lot of energy, but also causes pollution of atmospheric environment. The Guanzhong area is rich in renewable energy sources, such as biomass, geothermal energy, and solar energy, which can establish renewable distributed energy system (R-DES) in this study[6], [7].

With “Development Plan of Guanzhong Plain Urban Agglomeration”, the contradiction between backward power grid construction and economic development has become increasingly prominent. It sets new requirements for power grid construction. Considering the existing economic level and natural resources in this area, in order to ensure the safety and reliability of energy supply in Guanzhong area, R-DES was developed.

2.2. Modeling formulation
This paper will base on the interval linear programming, aiming at system economy, and considering the factors such as energy availability, devices matching and economics under the premise of satisfying the user load. Get the optimal configuration and optimal operating mode of the system. The goal of R-DES model is to minimize the total system cost. It depends on the following equation:

$$\min f = (C_{Capital} + C_{OM} + C_{Elec} + C - C_{Sub})$$  \hspace{1cm} (1)

(1) Devices cost:

$$C_{Capital} = 4/365 \times [\sum_i \sum_n \maxcap_{iu} \times PN_{iu} \times CapCost_{iu} \times IRate / \left(1 - 1/(1 + IRate) \right)^{T_{life}^C_i}] + $$

$$\sum_u \maxcap_{iu} \times PNC_u \times CapCostC_u \times IRate / \left(1 - 1/(1 + IRate) \right)^{T_{life}^C_u}$$  \hspace{1cm} (2)

(2) Operating cost:

$$C_{OM} = \sum_i \sum_h \sum_u \sum_i OM_{iu} \times G_{shiu} + \sum_i \sum_h \sum_u OMC_u \times CT_{shiu} + 4/365 \sum_i \sum_u OMS_u \times MaxES_{shiu}$$  \hspace{1cm} (3)

(3) Fuel cost:

$$C_{Fuel} = \sum_i \sum_h \sum_i P_{Fuel_{iu}} \times G_{shiu} / \eta_{i,u}$$  \hspace{1cm} (4)

(4) Power grid purchase cost:

$$C_{Elec} = \sum_i \sum_h P_{Elec_{h}} \times EP_{sh}$$  \hspace{1cm} (5)

(5) Subsidy:

$$C_{Sub} = 4/365 \sum_i \sum_u Sub_{iu} \times MaxCap_{iu} \times T_{life_i} + \sum_i \sum_h \sum_i \sum_u Sub_{shiu} \times G_{shiu}$$  \hspace{1cm} (6)

Subject to:

(1) Maximum power constraints for devices:

$$G_{shiu} \leq PN_{iu} \times \maxcap_{iu}$$  \hspace{1cm} (7)

$$CT_{shiu} \leq PNC_u \times \maxcap_{iu}$$  \hspace{1cm} (8)

$$\lambda G_{shiu=NG, a=heat} \leq G_{shiu=NG, a=elec}$$  \hspace{1cm} (9)

(2) Solar photovoltaic panel generation constraints:

$$G_{i, h, i=PV, u=elec} \leq PN_{i=PV} \times SA \times SI_{shiu} \times \eta_{i=PV, u}$$  \hspace{1cm} (10)

(3) Energy conversion devices conversion constraints:
\[ o_{u=cold} = \sum_{s} G_{s, u=heat}^\pm = C_{s, u=heat}^\pm \] (11)
\[ o_{u=elec} = \sum_{s} G_{s, u=elec}^\pm = C_{s, u=elec}^\pm \] (12)
\[ o_{u} = \sum_{s} G_{s, win, u}^\pm = C_{s, win, u}^\pm \] (13)

(4) Storage devices constraints:
Energy storage device at \( h = 1 \), which are expressed as follows:
\[ EStor_{s, h=1, u} = 0 \] (14)
\[ IStor_{s, h=1, u} \geq 0 \] (15)
\[ OStor_{s, h=1, u} = 0 \] (16)

When energy storage device is at \( h > 1 \), its operation can be represented by the following formula:
\[ EStor_{s, h=1, u} = EStor_{s, h=1, u} + \alpha_u \times IStor_{s, h=1, u} - OStor_{s, h=1, u} \] (17)
\[ 0 \leq EStor_{s, h=1, u} + \alpha_u \times IStor_{s, h=1, u} - OStor_{s, h=1, u} \leq MaxEStor_{u} \] (18)
\[ 0 \leq EStor_{s, h=1, u} \leq MaxEStor_{u} \] (19)

(5) Energy balance constraints:
\[ C_{s, h, u=elec} + E_{s, h, u=elec} + OStor_{s, h, u=elec} \geq IStor_{s, h, u=elec} + ED_{s, h, u=elec} + C_{s, h, u=elec} \times \gamma \] (20)
\[ C_{s, h, u=heat/cold} + OStor_{s, h, u=heat/cold} \geq IStor_{s, h, u=heat/cold} + ED_{s, h, u=heat} \] (21)

2.3. Data acquisition
The total construction area of the study area is 5.0 \times 10^4 \text{ m}^2. The cold and heat loads of users was simulated by Energy Plus 8.6 software and electrical loads was obtained through a questionnaire survey. The electric energy, cold and heat loads in this area are shown in Figure 1 and Figure 2. According to the "Standard Meteorological Data Book for Buildings", solar energy resources data are available[9]. The price of natural gas is 0.206 RMB/kWh and the electricity purchased from grid is 0.4983 RMB/kWh.

![Figure 1. The electric energy loads (kWh)](image1)

![Figure 2. The cold/heat load (kWh)](image2)

The main energy supply devices studied in this paper includes internal combustion engine generator set (NG), solar photovoltaic panel (PV), biomass boiler (BB), ground source heat pump (GP), absorption chiller (AC), heat exchanger (HE), ice-storage device (IS), heat storage tank (TS), battery (BA). Through the investigation of previous research literature and equipment products, the technical and financial characteristics of each equipment are summarized in Table 1[10].
The heat production of primary heat generating devices can be more widely used, which can promote the use and development of renewable energy. It is hoped that the state can increase subsidy so that renewable energy devices can be used more widely. From the analysis of this system, we can see that the energy demand of users is mainly provided by lithium bromide chillers. The battery storage efficiency is 0.75.

### Table 1. Technical and financial characteristics of equipment

| Devices | Cold Efficiency | Heat Efficiency | Electric Efficiency | Devices cost / RMB/kWh | Operating cost / RMB/kWh | Life / year |
|---------|-----------------|-----------------|---------------------|-------------------------|--------------------------|------------|
| NG      | 0.35            | 0.50            | —                   | [6625.6, 9234.4]        | [0.06, 0.08]              | 30         |
| PV      | —               | —               | 0.16                | [6475.2, 9024.8]        | [0.0084, 0.0012]          | 30         |
| BB      | —               | 0.85            | —                   | [1158.9, 1615.1]        | [0.07, 0.09]              | 20         |
| GP      | 5.00            | 4.40            | —                   | [8340.1, 11623.9]       | [0.0087, 0.0113]          | 20         |
| AC      | 1.20            | —               | —                   | [1230.7, 1715.3]        | [0.007, 0.009]            | 20         |
| HE      | —               | 0.98            | —                   | [167.9, 234.1]          | [0.0018, 0.0026]          | 20         |
| IS      | 0.65            | —               | —                   | [158.7, 221.3]          | [0.17, 0.23]              | 20         |
| TS      | —               | 0.90            | —                   | [75.2, 104.8]           | [0.15, 0.21]              | 20         |
| BA      | —               | 0.75            | —                   | [1488.9, 2075.1]        | [6.93, 9.67]              | 13.5       |

3. Results Analysis

3.1. Energy consumption and carbon emissions analysis

In this paper, R-DES study is mainly based on natural gas and supplemented by renewable energy. Through municipal power grid construction to provide support and supplement to this system, to maximize the use of resources. Therefore, the amount of carbon discharged from this system is lower than that of a centralized energy system. R-DES reduces electric supply of the power grid construction by 29.0%~63.6%, which can reduce the loss of electric energy in transmission process. The carbon emission reduction rate of this system is 4.0%~49.6%, which is because system use renewable energy to reduce carbon emissions.

3.2. Optimal operation mode analysis

From Figure 3 we can see that internal combustion generator set does not work in the spring and autumn, so electrical loads are mainly provided by municipal power grid construction. This is due to that there is no requirement for cold and heat loads in the spring and autumn. The peak in electricity consumption shows in the morning, noon, and evening. Before these moments arrive, this system will store electricity to reduce the capacity of the power generation devices. The battery storage efficiency is 0.75. In Figure 3, electricity flowing into battery is higher than electricity flowing out of battery. When solar radiation intensity reaches photovoltaic panel power generation requirement, electric energy is generated for use by users. In Figure 3, solar photovoltaic panels generate relatively large amounts of electricity in spring and summer, and the amount of electricity generated in winter is relatively small. From Figure 4 we can conclude that requirement for cold loads are mainly provided by lithium bromide chiller in summer. Cold loads do not fluctuate, and cold peak is usually concentrated in the time of period from 13:00 to 17:00.

From Figure 5 we can result that the heat production of primary heat generating devices includes biomass boiler and internal combustion generator set. After being converted to user through heat exchanger, since the conversion efficiency is 0.98. It can be seen from Figure 5 that there is no energy waste during heating process. In Figure 3, there is a serious overproduction of electricity in winter. With reference to Figure 5, this is because system generates heat while using internal combustion generating set to generate heat due to meet user's heat demand.

3.3. System cost analysis

Figure 6 is this system cost composition. The results show that devices cost accounting for approximately 50% of total cost in this system. Energy-generating devices consisting of internal combustion engine generator set and solar photovoltaic panels, resulting in higher system devices cost can be seen from Figure 6. In addition, the relevant policies of distributed energy system are imperfect, and subsidy is small. It is hoped that the state can increase subsidy so that renewable energy devices can be more widely used, which can promote the use and development of renewable energy.
Figure 3. Power balance model for typical day (kWh)

Figure 4. Cold balance model for typical summary day

Figure 5. Heat balance model for typical winter day (kWh)
Figure 6. System cost composition

4. Conclusion
This paper establishes R-DES optimization model combined with renewable energy using the method of interval linear programming. Cold and heat loads are calculated by the software PlusPlus8.6 software simulation and questionnaire survey. Under premise of meeting needs of users, this system devices capacity, devices cost, devices efficiency and fuel price are comprehensively considered. Combined with abundant renewable energy in rural areas, the optimal configuration and optimal operation mode of Guanzhong rural area are calculated by LINGO11.0 software. This paper establishes R-DES model using the method of interval linear programming. Through analysis of results, the following conclusions can be drawn: a) The R-DES has obvious energy saving and emission reduction effects. The power supply of power grid construction reduced by 29.0%~63.6%, and carbon emission reduction rate is 4.0%~49.6%; b) R-DES can establish in renewable energy-rich rural areas and promote construction of new countryside; c) Due to the high price of devices using renewable energy, which will lead to increase system costs. It is recommended that the government should increase subsidies for renewable energy devices; d) It is recommended that R-DES should be connected to power grid construction to improve energy efficiency.

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Appendix: List of Symbols

Subscripts:

s season, s= spr/ sum/ aut/ win
h hour, h=1, 2, ..., 24
i device types, i=1, 2, 3. 1. energy production devices; 2. energy conversion devices; 3. energy storage devices.

u energy types, u=cold/ heat/ electric

Decision variables:

$G_{s,h,i,u}$ production capacity devices produce energy, kWh
$CT_{s,h,u}$ energy conversion devices produce energy, kWh
$MaxEStor_{u}$ design capacity of energy storage devices, kWh
$EStor_{s,h,u}$ energy in energy storage devices, kWh
$IStor_{s,h,u}$ energy to enter the energy storage devices, kWh
$OStor_{s,h,u}$ energy flowing out of the energy storage devices, kWh
$EP_{s,h}$ power grid purchase, kWh

Parameters:

$C_{Capital}$ devices cost
$C_{om}$ running cost
$C_{Elec}$ power grid purchase cost
$C_{Fuel}$ fuel cost
$C_{Sub}$ subsidy cost
$MaxCap_{i,u}$ design capacity of production devices, kW
$MaxCapC_{u}$ design capacity of energy conversion devices, kW
$PN_{i}$ number of production devices
$PNC_{u}$ number of energy conversion devices
$PNS_{u}$ number of energy storage devices
$\text{CapCost}_{i,u}$production devices unit capacity devices cost, RMB/kW
$\text{CapCostC}_{u}$ energy conversion devices unit capacity devices cost, RMB/kW
$\text{CapCostS}_{u}$ energy storage devices unit capacity devices cost, RMB/kW
$\text{IRate}$ depreciation rate
$\text{Tlife}_{i}$ production devices life, year
$\text{TlifeC}_{u}$ energy conversion devices life, year
$\text{TlifeS}_{u}$ energy storage devices life, year
$OM_{i,u}$ production devices operation cost, RMB/kWh
$OMC_{u}$ energy conversion devices operation cost, RMB/kWh
$OMS_{u}$ energy storage devices operation cost, RMB/kWh
$\text{EP}_{s,h}$ power grid purchase, kWh
$\text{PFuel}_{i,u}$ fuel price, RMB/kWh
$\eta_{i,u}$ production devices productivity efficiency
$P_{Elec_{h}}$ hourly electricity price, RMB/kWh
$P_{Sub_{i,u}}$ one-time investment subsidy for devices, RMB/kWh
$P_{SubV_{i,u}}$ devices operation subsidy, RMB/kWh
$\lambda$ ratio of power generation and surplus heat of gas combustion engine, 0.7
$SA$ monolithic PV plate area, m²
$SI_{s,h}$ direct solar radiation, kW/m²
$\omega_{u}$ efficiency of energy conversion devices
$\alpha_{u}$ efficiency of energy storage devices
$ED_{s,h,u}$ user loads, kWh
$\gamma$ power dissipation factor of absorption chillers