Multi-objective optimization design of regional integrated energy system

Xueliang Li1, Kuihua Wu1, Lujie Qi1, Can Cui1, Dunnan Liu2 and Chen Li2*

1Economic & Technology Research Institute State Grid Shandong Electric Power Company, Jinan, Shandong, 250021, China
2School of Economics and Management, North China Electric Power University, Beijing, 102206, China
*Corresponding author’s e-mail: 1037646838@qq.com

Abstract. With the continuous development and progress of human society, the exploitation and utilization of fossil energy has also increased rapidly. With the intensification of the energy crisis and the continuous deterioration of environmental problems, it is urgent to find an energy-saving and environmentally-friendly Energy supply methods to replace traditional energy supply systems with high energy consumption and high pollution. The regional integrated energy system, by integrating multiple energy types and energy conversion equipment, can realize the stepwise and efficient use of energy, which is one of the important ways to solve the above problems. The performance of a regional integrated energy system is closely related to its planning and operation. Without proper system configuration and appropriate operating strategies, the system will not be able to achieve its due benefits. Therefore, it is urgent to propose comprehensive energy planning and operation optimization methods.

1. Introduction
As the global energy crisis and environmental pollution problems continue to increase, people are paying more and more attention to energy conservation and emission reduction. Various renewable energy sources[1] can be used in integrated energy systems, such as wind energy, solar energy, biomass energy, geothermal energy, etc.[2–5] And through the coupling of different energy systems, the goal of improving energy efficiency and reducing pollution emissions has been widely recognized as one of effective measures to solve energy and environmental problems, and these measures have been vigorously developed in many countries.

The application of a regional integrated energy system can not only bring obvious economic benefits, but also great energy and environmental benefits, which are consistent with the development needs and trends of human society. In terms of economic benefits, evaluation indicators such as total operating cost, annual equivalent total cost, annual equivalent cost savings, life cycle cost, and investment recovery period are usually used[6]. Energy efficiency is generally assessed using primary energy consumption and primary energy savings[7,8]. In terms of environmental benefits, carbon dioxide emission reductions and life-cycle pollution emissions are defined for evaluation[9]. In addition, other evaluation indicators such as operational reliability and energy efficiency are also commonly used to evaluate the performance of distributed energy systems[10]. In the previous optimization studies, most of them took economic indicators as the sole objective of investor optimization planning, and ignored other benefits of the system. Zhou et al.[11] proposed a two-stage stochastic optimization method for
distributed energy system planning problems, and Guo et al.[12] proposed a two-stage optimization method for combined heat and power systems.

Therefore, this article focuses on the multi-objective optimization design of the regional integrated energy system, and optimizes the planning and operation of the system under multiple optimization objectives. The multi-attribute decision-making method based on evidence reasoning[13] is used to implement the decision of the multi-objective optimization problem. The decision-making method based on evidence reasoning is a multi-attribute decision-making method proposed by multiple scholars such as Professor Yang Jianbo, Professor Xu Dongling and Madan G. Singh[14,15] in order to solve the multi-objective problem with uncertain factors. Establish a multi-objective planning and operation optimization model for the economic, environmental and energy efficiency of regional integrated energy systems.

2. Basic architecture of a district energy system
The system structure of a regional integrated energy system can be established as shown in Figure 1. The basic architecture design of a regional integrated energy system must fully consider the energy requirements of the user side, the local available energy resources, the climatic conditions of the area, the types of equipment that can be used to form the system, and the actual constraints such as the size of the installation site, etc. Factors can form a complete system framework and be optimized to obtain the optimal energy supply system for the region.

![Figure 1. Basic framework of a regional integrated energy system](image)

3. Multi-objective optimization design model
This paper uses a two-stage optimization method to optimize. The first stage is to optimize the type and capacity of the equipment in the system, considering three different goals, namely economic goals, energy saving goals and environmental protection goals; the second stage is to optimize the hourly output of equipment in the system, considering only economics aims.

3.1. Objective function
This article mainly considers the economic benefits, environmental protection benefits, and energy benefits of regional integrated energy systems, so three goals are set here to evaluate these three benefits of the system.
1) Economic goals
The annual total cost is used as the objective function of the optimization at the planning level. The total annual cost is the sum of the annual equivalent investment cost $C_{\text{inv}}$ and the annual operation and maintenance cost $C_{\text{ope}}$. It is calculated by the following formula:

$$C_{\text{total}} = C_{\text{inv}} + C_{\text{ope}}$$  \hspace{1cm} (1)

The annual equivalent investment cost $C_{\text{inv}}$ is the cost value of the system's total investment cost that is allocated to each year in the operating cycle by an equal amount, which is calculated as follows:

$$C_{\text{inv}} = \sum_{i=1}^{I} (a_i c_i P_{i}^{\text{rated}} + f_i c_i P_{i}^{\text{rated}})$$  \hspace{1cm} (2)

Where $I$ is the total number of equipment; $P_{i}^{\text{rated}}$ is the rated capacity of the equipment; $c_i$ is the unit investment cost of the equipment; $f_i$ is equipment fixed operation and maintenance cost coefficient; $a_i$ is the annual equivalent investment conversion factor of the equipment.

$$a_i = \frac{m(1+m)^N}{(1+m)^N-1}$$  \hspace{1cm} (3)

Where $m$ is the annual interest rate and $N$ is the life of the equipment.

Operating costs include equipment operation and maintenance costs and fuel costs, which can be calculated from the following formula:

$$C_{\text{ope}} = C_{\text{om}} + C_{\text{fuel}} = \sum_{h=1}^{H} \sum_{i=1}^{I} a_i P_{i}^{h} + \sum_{h=1}^{H} \sum_{j=1}^{J} u_{j}^{h} E_{j}^{h}$$  \hspace{1cm} (4)

In the formula, $H$ is the total annual operating hours of the equipment; $a_i$ is the unit's variable operation and maintenance cost of the equipment; $P_{i}^{h}$ is the output value of the equipment $i$ in the $h$-th hour; $J$ is the total type of input energy; $u_{j}^{h}$ is the price of the $j$-th energy source in the $h$-th hour; $E_{j}^{h}$ is the use amount of the $j$-th energy source in the $h$-hour.

2) Energy saving goals
The annual primary energy consumption is used as an indicator to measure its energy efficiency. By converting primary energy into equivalent standard coal consumption, the total equivalent standard coal consumption is the annual primary energy consumption, which can be calculated as follows:

$$F = \sum_{h=1}^{H} \sum_{j=1}^{J} \lambda_j E_{j}^{h}$$  \hspace{1cm} (5)

In the formula, $\lambda_j$ is the standard coal consumption conversion coefficient of the $j$th energy source.

3) Environmental goals
The carbon dioxide emissions are used as indicators to measure its environmental benefits. Here, the pollution caused by burning natural gas and diesel and the pollution generated by coal-fired power generation in the power grid are mainly considered. Therefore, the total annual pollution emissions are calculated as follows:

$$R = \sum_{h=1}^{H} \sum_{j=1}^{J} \mu_j E_{j}^{h}$$  \hspace{1cm} (6)

In the formula, $\mu_j$ is the unit emission coefficient of the $j$-th energy source. If it is a non-polluting energy source such as solar energy, its value is 0.

3.2. Multi-objective particle swarm optimization
Common multi-objective optimization algorithms include multi-objective evolutionary algorithm (MOEA), second-generation non-dominated sorting genetic algorithm (NSGA-II), and multi-objective particle swarm optimization (MOPSO). Among them, MOPSO has fast convergence speed and is suitable for continuous variables. It has the advantages of optimization and short calculation time, so this paper uses it as an optimization algorithm. The specific steps of the multi-objective particle swarm algorithm are as follows:

Step 1: Enter various parameters of the integrated energy system;
Step 2: Initialize the particle members of the multi-objective particle swarm algorithm;
Step 3: Calculate the fitness value of each particle;
Step 4: Compare the pros and cons of the fitness values of each member and update the Pareto front;
Step 5: Update the population members and recalculate from step 2 until the maximum number of iterations is reached.
4. Practical example verification

4.1. System parameter setting

The proposed multi-objective optimization design model of the regional integrated energy system was applied to the energy supply of a park in southern China. Taking the three objectives of system economic benefit, environmental benefit and energy benefit as optimization targets, the multi-objective particle swarm optimization algorithm is used to perform optimization calculations to obtain a series of feasible solutions. Finally, the decision-making method based on evidence reasoning is used to obtain the optimal system. Configuration. In the solution process, it was found that the cost and pollution of different schemes are quite different, and the primary energy consumption is very close. Therefore, cost and pollution are considered as first-level important goals, and energy consumption is considered as a second-level important goal. In the first stage, In multi-objective optimization, cost and pollution are used as optimization goals, and energy consumption is involved in the optimization as an attribute of the decision-making stage.

Table 1. Energy pollution emission factor and standard coal consumption conversion factor.

| Project            | Pollution emission factor (kg/kWh) | Conversion factor of standard coal consumption (kg/kWh) |
|--------------------|----------------------------------|--------------------------------------------------------|
| Electricity        | 0.968                            | 0.32                                                   |
| Natural gas(GT GE) | 0.184                            | 0.121                                                  |
| Natural gas(GB00)  | 0.126                            | 0.121                                                  |

The pollution emission coefficient of energy and its conversion coefficient equivalent to standard coal are shown in Table 1. Here, the pollution emissions generated when natural gas is burned and used by gas turbine, gas internal combustion engine and gas boiler are different. The available area of solar energy is 80000m². The surplus power of the regional integrated energy system is allowed to be sold to the power grid, and the on-grid tariff is 0.7 times the current grid power tariff. The number of iterations set by the multi-objective particle swarm optimization algorithm is 500, and the population size is 100.

4.2. Optimization results and analysis

There is a conflicting relationship between the economy and environmental protection of the capacity allocation plan of the multiple regional integrated energy systems. When the total cost is lower, the corresponding pollution emissions are higher.

Table 2. The target values of the 8 solutions obtained by multi-objective optimization

| Program | Cost (10^7 yuan) | Emissions (10^7 kg) | Energy consumption (10^7 kg) | Power purchase (10^7 kWh) | Natural gas (10^7 kWh) | Electricity sale (10^7 kWh) |
|---------|------------------|---------------------|------------------------------|--------------------------|------------------------|-----------------------------|
| S1      | 10.16            | 5.59                | 2.80                         | 2.53                     | 1.64                   | 0.38                        |
| S2      | 10.44            | 5.08                | 2.79                         | 1.77                     | 18.33                  | 0.55                        |
| S3      | 10.53            | 4.86                | 2.83                         | 1.21                     | 20.09                  | 1.06                        |
| S4      | 10.63            | 4.70                | 2.75                         | 1.09                     | 19.78                  | 0.84                        |
| S5      | 10.78            | 4.59                | 2.81                         | 0.68                     | 21.34                  | 1.25                        |
| S6      | 11.05            | 4.55                | 2.85                         | 0.48                     | 22.19                  | 1.47                        |
| S7      | 11.38            | 4.52                | 2.83                         | 0.49                     | 21.99                  | 1.38                        |
| S8      | 11.79            | 4.50                | 2.83                         | 0.43                     | 22.21                  | 1.42                        |

In order to comprehensively consider and weigh the cost, emissions, and energy consumption of the system capacity allocation scheme, here, a multi-attribute decision method based on evidence reasoning is used to solve the final system capacity allocation scheme from the eight alternatives to be selected. After sorting the values of the attributes of the selected scheme, the attributes of each scheme can be evaluated.
Considering that economic benefits are the most important indicator for investors, the weight coefficients of economic benefits should be appropriately increased when allocating weight coefficients to various targets. Therefore, the weights assigned to the three attributes of cost, pollution and energy consumption to be evaluated are, in order, 0.5, 0.4, and 0.1. In addition, the evaluation level is set to $H = \{\text{Very poor, Poor, Fair, Good, Very Good, Uncertain}\}$. In order not to lose generality, the weight of the uncertainty level of each attribute is set to 0.1. Through the evidence fusion method in evidence reasoning, the total confidence evaluation of each candidate can be obtained. The final evaluation results are shown in Table 3. In order to more intuitively evaluate the pros and cons of these eight schemes, the utility distribution is used to map the confidence distribution into utility values, and the maximum, minimum, and average utility values of each scheme are obtained, as shown in Table 4. According to the average utility value of these 8 schemes, the ranking can be $s4 > s5 > s1 > s2 > s3 > s6 > s7 > s8$. Therefore, Option 4 is the optimal capacity configuration plan for the district cooling, heating and power cogeneration system.

| Program | Very poor | Poor | Fair | Good | Very good | Uncertain |
|---------|-----------|------|------|------|-----------|-----------|
| S1      | 0.1820    | 0.0903 | 0.1560 | 0.0744 | 0.4027    | 0.0946    |
| S2      | 0         | 0.1103 | 0.5387 | 0.1094 | 0.1561    | 0.0856    |
| S3      | 0.0145    | 0.1582 | 0.3993 | 0.2856 | 0.0539    | 0.0886    |
| S4      | 0         | 0      | 0.5182 | 0.1485 | 0.2479    | 0.0853    |
| S5      | 0.0145    | 0.1986 | 0.2765 | 0.3486 | 0.0731    | 0.0887    |
| S6      | 0.1074    | 0.3668 | 0.1317 | 0.1449 | 0.1551    | 0.0941    |
| S7      | 0.1436    | 0.3236 | 0.2380 | 0.0753 | 0.1255    | 0.0913    |
| S8      | 0.4862    | 0.0880 | 0.1337 | 0.0251 | 0.1757    | 0.0913    |

| Utility value | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---------------|----|----|----|----|----|----|----|----|
| Max           | 0.6779 | 0.6695 | 0.6602 | 0.7445 | 0.6797 | 0.5732 | 0.5250 | 0.3927 |
| Min           | 0.5833 | 0.5839 | 0.5716 | 0.6592 | 0.5910 | 0.4791 | 0.4337 | 0.3014 |
| Average       | 0.6306 | 0.6267 | 0.6159 | 0.7019 | 0.6354 | 0.5261 | 0.4793 | 0.3470 |

Comparing the optimal CCHP system obtained by multi-objective optimization with the economical CCHP system obtained by single-objective optimization, it can be found that the total annual cost has increased by 4.6%, but the pollution emission has decreased by 15.9%, and the primary energy consumption has decreased by 1.8%. Comprehensive evaluation of the economic, environmental protection and energy efficiency of these two systems, the comprehensive performance of the multi-objective optimal CCHP system is better.

5. Conclusion
This paper establishes a multi-objective planning and operation optimization model for a regional integrated energy system. At the planning level, the system's economic and environmental benefits and energy efficiency are the optimization goals, and the system equipment type and capacity are optimized. At the operation level, the minimum operation and maintenance costs are still the optimization goals for the equipment in operation Hourly output for reasonable allocation. The multi-objective optimization method is used to optimize to obtain the Pareto optimal solution set, and then the multi-attribute decision-making method based on evidence reasoning is used to select the optimal system solution. The validity of the multi-objective planning and operation optimization method is verified through the analysis of the results of examples.
Acknowledgement
Funded by the Science and Technology Project of the State Grid Corporation Headquarters ("Research on Coordinated Planning, Optimal Scheduling and Evaluation System of Integrated Energy System from the" Re-electrification "Perspective)

References
[1] Ji, P., Zhou, X.X., Song, Y.T., Ma, S.Y., Li, B.Q. (2013), Review and Prospect of Regional Renewable Energy Planning Models. J. Grid Technology, 37(08): 2071-2079.
[2] Jing, Y.Y., Bai, H., Zhang, J.L. (2012) Multi-objective Optimal Design and Operation Strategy Analysis of Solar Combined Heat and Power System. J. Chinese Society for Electrical Engineering, 32(20): 82-87+143.
[3] Zhou, R.J., Yin, Q., Kang, X.W., Li, S.J., Chen, R.X., Wang, J. (2015) Optimal Operation Control of Wind Power Combined with Cogeneration System. J. Journal of Electric Power Science and Technology, 29(03): 45-51.
[4] Wei, D.J., Sun, B., Zhao, F., Zhang, C.H. (2015) Multi-objective Optimal Design and Operation Analysis of Small Biomass Biogas Combined Cooling and Heat and Power System. J. Automation of Electric Power Systems, 39(12): 7-12.
[5] Li, F., Zhao, X.L., Fu, L., Zhang, S.G. (2010) New Cogeneration System Using Geothermal Energy and Application Analysis. J. Building science, 26(10): 131-135.
[6] Jing, Y.Y., Bai, H., Wang, J.J. (2012) A fuzzy multi-criteria decision-making model for CCHP systems driven by different energy sources. J. Energy Policy, 42: 286–296.
[7] Zhang, T., Zhu, T., Gao, N.P., Wu, L. (2015) Research on Optimized Design and Multi-index Comprehensive Evaluation Method of Distributed Cooling, Heating and Electricity Energy System. J. Chinese Society for Electrical Engineering, 35(14): 3706-3713.
[8] Jiang, R.H., Zeng, R., Li, H.Q., Zhang, G.Q., Yang, M.L., Xu, Y.J., (2016) Multi-objective Optimization and Evaluation of Distributed Cogeneration System Considering Climatic Conditions and Building Types. J. Chinese Society for Electrical Engineering, 36(12): 3206-3214.
[9] Jing, Y.Y., Zhang, C.F. et al. (2008) Integrated evaluation of distributed triple-generation systems using improved grey incidence approach[J]. Energy, 33(9): 1427–1437.
[10] Chen, B.S., Liao, Q.F., Liu, D.C., Wang, W.Y., Wang, Z.Y., Chen, S.Y. (2018) Comprehensive evaluation indicators and methods for regional integrated energy systems. J. Automation of Electric Power Systems, 42(04): 174-182.
[11] Zhou, Z., Zhang, J., Liu, P., et al. (2013) A two-stage stochastic programming model for the optimal design of distributed energy systems. J. Applied Energy, 103: 135–144.
[12] Guo, L., Liu, W., Cai, J., et al. (2013) A two-stage optimal planning and design method for combined cooling, heat and power microgrid system. J. Energy Conversion and Management, 74: 433–445.
[13] Wei, F., Wu, Q.H., Jing, Z.X., Chen, J.J., Zhou, X.X. (2016) Optimal unit sizing for small-scale integrated energy systems using multi-objective interval optimization and evidential reasoning approach. J. Energy, 111: 933-946.
[14] Yang, J.B., Singh, M.G. (1994) An evidential reasoning approach for multiple-attribute decision making with uncertainty. J. IEEE Transactions on systems, Man, and Cybernetics, 24(1): 1–18.
[15] Yang, J.B., Xu, D.L. (2002) On the evidential reasoning algorithm for multiple attribute decision analysis under uncertainty. J. IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans, 32(3): 289–304.