Multi-objective Optimization of Park-level Integrated Energy System: Model and Analysis

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Abstract. Using an integrated energy system can increase the proportion of renewable energy and comprehensive energy utilization efficiency, which help solve problems such as environmental pollution, carbon emissions, and depletion of fossil energy. The actual construction and operation of an integrated energy system need to consider not only the economy, but also the energy consumption and carbon emissions. Therefore, it is necessary to establish a multi-objective optimization model of the integrated energy system to achieve the combination of economics, energy saving and environmental protection for the system is optimal. In this paper, a multi-objective optimization model for an integrated energy system is established, and the influence of different decision makers' preferences on the optimization results is studied through the model.

1. Introduction
To solve the problems of environmental pollution and climate warming, countries around the world are vigorously developing renewable energy. With the advancement of renewable energy technology and information technology, the research and application of distributed integrated energy systems (IES) that use renewable energy on a large scale have become an important research hotspot in the current energy industry [1]. The IES includes the whole processes of power supply, grid, load, and energy storage. The “energy source” includes wind, solar, gas turbine, and other energy supplies. The “load” includes electricity, gas, cooling, and heat. In IES, there are various energy grids, such as gas grid and power grid, and various energy storage equipment in the area. The system operates complexly. Therefore, it is necessary to establish an optimization model for the IES to achieve the optimal operation mode that meets specific objectives.

At present, the operation optimization of the IES is mainly single-objective optimization. Sun et al [2] has constructed an economical optimal model of the park’s IES including electricity, heat, cooling, and gas with the total cost of construction and operation as the target. Feng et al [3] using the distributed robust optimization method, constructed a day-to-real-time two-stage optimization model for a biogas-wind-solar energy system with minimizing cost. Wang et al [4] taking the minimum total operating cost as the goal, established a multi-time scale optimization model for a regional IES based on the multi-scene stochastic programming and model predictive control methods. Ai et al [5] has established the optimization model for an electric-heat-gas coupling system based on demand response with the goal of minimum integrated operating cost.

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Most studies mainly only consider the objective of economic, because the economical factor determines whether the project can be implemented in actual [6]. However, the IES aims to reduce environmental pollution, utilization of fossil energy and carbon emissions. China joined the Paris Climate Change Agreement and promised to achieve four major goals including peak carbon dioxide emissions in China around 2030 [7]. To achieve this goal, we need to reduce the use of fossil energy to achieve the goal of reducing carbon emissions. The report of the 19th National Congress of the Communist Party of China proposed to advance the revolution of energy production and consumption, build a clean, low-carbon, safe and efficient energy system, and pointed out the direction of China’s energy transition [7]. Therefore, when constructing and operating an IES, not only economic aspect, but also emission reduction and energy saving aspects need to be considered. And the decision preference of the three objectives should be studied as it influences the optimization results.

In this study, the three major objectives of economy, carbon emissions and energy saving are considered comprehensively. An optimization model for an IES which includes gas-fired generating units, lithium bromide units, ground source heat pump units, air source heat pump units, electrical batteries, photovoltaics was built. The system also includes a variety of energy types such as electricity, gas, cooling/heating, and whole processes of energy supply, grid, load, and energy storage. Besides, the impact of the decision preferences the optimization results was studied through the model.

2. Multi-objective of IES

For the operation of IES, we consider three objectives such as economy, energy-saving and environmental protection. Different preferences of decision makers can lead to completely different results cause of the Constraints among objectives. The definitions of different objectives and a method of multi-objective optimization considering the decision maker’s preferences are described as below.

2.1. economy

Economy is a direct driver of the development of IESs. The objective defined as minimizing the cost of electricity and gas while ignoring the initial investment and depreciation fees.

\[
 f_1(x) = p_e P_e(x) + p_g P_g(x)
\]

where \(x\) is decision variable, \(P_e\) is time of use (TOU) power price, \(P_e(x)\) is TOU power from grid. \(P_g(x)\) is the amount of natural gas consumed, \(P_g\) is gas price.

2.2. energy-saving

The practical implication of this objective is that consuming fewer energy resources to meet the same energy requirements. Calculate it by minimizing the coal consumption converted from input energy.

\[
 f_2(x) = \alpha_{e2coal} P_e(x) + \alpha_{g2coal} P_g(x)
\]

The coefficient of electricity to standard coal \(\alpha_{e2coal}\) is token into account by equal value because electricity is not a primary energy source. \(\alpha_{g2coal}\) is the conversion coefficient of gas to standard coal.

2.3. environmental protection

This objective considers the effect of climate changes by energy utilization. It means minimizing CO\(_2\) emissions converted from input energy. Where \(\alpha_{e2co2}\) is the coefficient of electricity to CO\(_2\) emissions, while \(\alpha_{g2co2}\) is gas to CO\(_2\) emissions.
2.4. a method of multi-objective optimization
It is a multi-objective optimization if considering economy, energy-saving and environmental protection simultaneously, which could be described as follow.

\[ f(x) = \alpha_{e\text{co}_1} P_e(x) + \alpha_{e\text{co}_2} P_e(x) \]  

(3)

Ignoring the preference of the decision maker, a set of optimal solutions, namely the Pareto frontier, can be obtained when solving this problem. It’s not enough to get a set of solutions cause practical problems often require a definite answer. One approach is to transform the multi-objective problem into a single-objective problem by considering the decision maker’s preference. The weighted sum method can give consideration to the effect of different targets [8]. Where, the linear weighted sum method enables each component to approach its optimal value according to its importance. Furthermore, normalization method is used to eliminate the error caused by too large difference among the optimal values of each objective in this paper. Its function is expressed as follows:

\[ g(x) = \sum_{i=1}^{k} \alpha_i \left[ f_i(x)/f_i^* - 1 \right] \]  

(5)

where \( \alpha_i \) is the weight coefficient of each objective. How to determine the \( \alpha_i \) is the key point in multi-objective optimization. According to Formula (5), this paper focuses on the study of the effects of different weight coefficients.

3. Models
This section describes the consist of typical IES, explains variables and constraints of the optimization.

3.1. typical IES
A typical IES includes multiple links such as source, network, charge and storage, etc. Typical equipment in the system includes combined cold, heat and power units, electric refrigerating units, renewable energy generating units and energy storage devices.

Taking the summer operation mode as an example, to find the optimal operation scheme satisfying the objective function, it is necessary to construct the optimization problem from the level of individual device and system.

3.2. Device level constraint

3.2.1. CCHP. This device consists of a gas-fired generator (GG) and a lithium bromide absorption chiller (LBAC). To simplify the model, define a constant \( \lambda \) as the ratio of refrigeration power generated by exhaust to GG power. The refrigeration power generated by the supplementary combustion is calculated separately. Therefore, there are two kinds of continuous variables \( P_{e,\text{gg}} \) and \( P_{e,\text{sup}} \), which represent the power generation of GG and the refrigeration power generated by the supplementary combustion, respectively. Also, there are two Boolean variables, \( B_{e,\text{gg}} \) and \( B_{e,\text{sup}} \), represent the working state of the GG and LBAC supplementary, respectively.

\[ b_{e,\text{gg}} P_{\text{min}} \leq P_{e,\text{gg}} \leq b_{e,\text{gg}} P_{\text{max}} \]  

(6)
$b_{c,sup}^i P_{c,sup}^{min} \leq P_{c,sup}^i \leq b_{c,sup}^i P_{c,sup}^{max}$

(7)

$P_{c,lbac}^i = \lambda P_{e,gg}^i + P_{e,sup}^i$

(8)

$P_{g,cchp} = 3.6E6 \times t \left( P_{e,gg}^i / q_{gas} \eta_{gg} \right) + \eta_{s,gg} P_{e,sup}^i$

(9)

where, superscript $i$ is the index of unit period, which satisfies $i \in \{0,1, \ldots, T-1\}$, $T$ is the number of unit period in the control time. $P_{e,gg}^{min}$ and $P_{e,gg}^{max}$ are the minimum and maximum power of generator. $P_{c,sup}^{min}$ and $P_{c,sup}^{max}$ are the minimum and maximum refrigeration power generated by supplementary combustion. $\lambda$ is the thermoelectric ratio. $P_{c,lbac}^i$ is the total refrigeration power of LBAC. $t$ is the length of a unit period. $q_{gas}$ is the low heat value of natural gas. $\eta_{gg}$ is the gas power generation efficiency, $\eta_{s,gg}$ is the fuel gas transformation efficiency of LBAC. $P_{g,cchp}$ is the total gas consumption of CCHP.

3.2.2. ES. Energy storage includes battery energy storage (BES) and water storage (WS). Take BES for an example. $P_{e,bes,ch}^i$ and $P_{e,bes,dis}^i$ are set as charging power and discharging power, respectively. $b_{e,bes,ch}^i$ and $b_{e,bes,dis}^i$ represent charging state and discharging state, respectively. Constraints are as follows:

$b_{e,bes,ch}^i P_{e,bes,ch}^{min} \leq P_{e,bes,ch}^i \leq b_{e,bes,ch}^i P_{e,bes,ch}^{max}$

(10)

$b_{e,bes,dis}^i P_{e,bes,dis}^{min} \leq P_{e,bes,dis}^i \leq b_{e,bes,dis}^i P_{e,bes,dis}^{max}$

(11)

$P_{e,bes}^i = -P_{e,bes,ch}^i + P_{e,bes,dis}^i$

(12)

$b_{e,bes,ch}^i + b_{e,bes,dis}^i \leq 1$

(13)

$SOC_{bes}^i = SOC_{bes}^{i-1} + \left( t \times \eta_{bes,ch} \times P_{e,bes,ch}^i - t \times P_{e,bes,dis}^i / \eta_{bes,dis} \right) / E_{bes,max}$

(14)

$SOC_{bes}^{min} \leq SOC_{bes}^i \leq SOC_{bes}^{max}$

(15)
where, $P_{\text{min}}$ and $P_{\text{max}}$ represent the minimum and maximum charging power. $P_{\text{min}}$ and $P_{\text{max}}$ represent the minimum and maximum discharge power. $P_{e,\text{bes}}$ is the power of the BES, where the charge is negative and the discharge is positive. The $SOC_{\text{bes}}$ is the state of charge of the BES.

3.2.3. **HP**. Electric refrigerating units include ground source heat pump (GSHP) and air source heat pump (ASHP). Take GSHP as an example. The refrigeration power $P_{e,\text{gshp}}$ is a continuous variable, and the working state $b_{e,\text{gshp}}$ is a Boolean variable. The constraints are as follows:

$$b_{e,\text{gshp}} P_{\text{min}} \leq P_{i,\text{gshp}} \leq b_{e,\text{gshp}} P_{\text{max}}$$ \hspace{1cm} (16)

$$P_{e,\text{gshp}} = P_{i,\text{gshp}} / COP_{\text{gshp}}$$ \hspace{1cm} (17)

where, $P_{\text{min}}$ and $P_{\text{max}}$ represent the minimum and maximum refrigeration power of GSHP. $COP_{\text{gshp}}$ is the energy efficiency coefficient of GSHP, and $P_{e,\text{gshp}}$ is the power consumed by GSHP.

3.2.4. **Grid**. There are upper and lower limits of grid power supply:

$$b_{e,\text{grid}} P_{\text{min}} \leq P_{e,\text{grid}} \leq b_{e,\text{grid}} P_{\text{max}}$$ \hspace{1cm} (18)

where, $P_{\text{min}}$ and $P_{\text{max}}$ are the minimum and maximum power from grid, and $b_{e,\text{grid}}$ is the state of connecting grid.

3.3. **System-level constraint**
The system level constraints are electric balance, cold balance and gas balance.

$$0 = P_{e,\text{bes}} + P_{e,\text{gg}} + P_{e,\text{pv}} + P_{e,\text{grid}} + P_{i,\text{gshp}} + P_{e,\text{ashp}} + P_{e,\text{ws}} + P_{e,\text{load}}$$ \hspace{1cm} (19)

$$0 = P_{e,\text{bes}} + P_{e,\text{gshp}} + P_{e,\text{ashp}} + P_{e,\text{ws}} + P_{e,\text{load}}$$ \hspace{1cm} (20)

$$0 = P_{g,\text{cchp}} + P_{g,\text{gas}}$$ \hspace{1cm} (21)

where, subscript $e$ represents electric power, $c$ is refrigeration power, and $g$ is gas consumption. For each variable, consumption is negative and production is positive.
3.4. Optimization problem construction
To sum up, for a typical IES, constraints are established from the device level and system level. The decision variable is:

\[
\mathbf{x} = [P_{i_{e,gg}}^{p}, P_{i_{e,lep}}^{p}, P_{i_{e,ges,eh}}^{p}, P_{i_{e,ges,dis}}^{p}, P_{i_{e,gshp}}^{p}, P_{i_{e,shp}}^{p}, P_{i_{e,ws,eh}}^{p}, P_{i_{e,ws,dis}}^{p}, P_{i_{e,grid}}^{p}, b_{i_{e,gg}}^{b}, b_{i_{e,lep}}^{b}, b_{i_{e,ges,eh}}^{b}, b_{i_{e,ges,dis}}^{b}, b_{i_{e,gshp}}^{b}, b_{i_{e,shp}}^{b}, b_{i_{e,ws,eh}}^{b}, b_{i_{e,ws,dis}}^{b}, b_{i_{e,grid}}^{b}]
\]  

(22)

where, \( i \in \{0,1, \ldots , T-1\} \). Assuming that the number of each device is 1, then \( \mathbf{x} \in \mathbb{R}^{18T} \). The improved linear weighting method in Section 1 is used to construct the objective function to generate the multi-objective optimization problem of IES. This problem is Mixed Integer Linear Programming (MILP).

4. Case Study
This section takes a demonstration park of IES in Beijing as an example to do the multi-objective optimization study. In the model, the cooling comes from gas direct-fired lithium bromide units, ground source heat pumps, air source heat pumps, and water storage tanks; the power comes from gas turbines, electrical batteries, photovoltaic system, and power grid; and the gas comes from the gas pipeline.

4.1. Typical daily load
A typical daily load in summer is analysed in this case study. The typical daily load in summer is shown in the figure below, and the load demand is used as a case setting parameter for this case study.

![Figure 1. Typical Daily Load in Summer.](image)

4.2. Influence of decision preference on optimization results
In this study, the linear weighted method was used for the objective function in the multi-objective optimization model. The weight coefficients setting for the three targets were divided into three groups in order to study the influence of the decision preference on the multi-objective optimization result. In each group, let a single target weight change and keep the other two targets equal.

4.2.1. Influence of economic weight. The results of normalized indexes of economic, environmental protection and energy saving of the optimization are shown in Figure 2. \( f \) and \( f^* \) are the optimal values under multi-objective and single-objective, respectively.
As shown in figure 2, when the weight of economic objective increases, the operating cost decrease, and the CO$_2$ emission and coal consumption increase, which means that the economic goal is mutually constrained with the environmental protection and energy saving goals. When the economic weight increases from 0 to 0.4, the operating cost decreases by a large margin, while the CO$_2$ emissions and coal consumption increase not significantly. When the economic weight increases from 0.6 to 0.8, the operating cost decreases, but the CO$_2$ emission increases sharply. So, the weight of economic objective should be selected in the range of 0.4-0.6, which can ensure that the operating cost is relatively low, and keep the CO$_2$ emission and coal consumption at a low level.

As shown in Figure 3, the economic weights of 0, 0.4, and 0.8 were selected for comparison. When the weight of economic objective increases, the system inclines to use power from the grid to replace CCHP at 0-7 am, and use power from the grid to charge the batteries at 15 and 17 pm. This is because the cost of electricity from the grid is lower than that from CCHP during the low power consumption period. For cooling, when the weight of economic objective increases, the system prefers to use ground-source heat pumps and air-source heat pumps, rather than CCHP and water tanks.

![Figure 2. Results of Normalized Index under Different Weight of Economic Objective.](image)

![Figure 3. Load Supply and Demand under Different Weight of Economic Objective.](image)
4.2.2. **Influence of energy-saving weight.** The results are shown in Figure 4. When the weight of energy-saving objective is gradually increased, the coal consumption is reduced, the CO₂ emissions are first reduced and then slightly increased, and the operating costs are increased. When the energy-saving weight increases from 0.6 to 1.0, the coal consumption is almost unchanged, while the CO₂ emission rebounds, and the operating cost increases significantly. Therefore, the weight of the energy saving objective needs to be controlled within 0.6.

**Figure 4.** Results of Normalized Index under Different Weight of Energy Saving.

The energy consumption in summer is mainly caused by refrigeration equipment. As shown in Figure 5, the cooling load supply under the energy-saving weights of 0, 0.4, and 1.0 are given. When the energy-saving weight is increased, the system will reduce using the air source heat pumps and CCHP, and use the ground source heat pumps for cooling.

**Figure 5.** Cooling Load under Different Weight of Energy-Saving.

4.2.3. **Influence of environmental protection weight.** The results are shown in Figure 6. From the result, the environmental protection target weight should be set in the range of 0.3 to 0.5. Electric load under different weight of environmental protection is shown in figure 7.
Figure 6. Results of Normalized Index under Different Weight of Environmental Protection.

Figure 7. Electric Load under Different Weight of Environmental Protection.

The electric load supply under the environmental protection weights of 0.2, 0.8, and 1.0 are given. When the weight of environmental protection objective increases, the system will reduce using the power from the grid and CCHP, and use more power from batteries.

5. Conclusion
In this study, the normalized linear weighted method is used to establish a multi-objective optimization model, which considers objectives of not only economic, but also energy-saving and environmental protection for an integrated energy system. And through this model, the influence of different objective weights on the optimization results are discussed. Through calculations and analysis, the following conclusions are obtained:

Different plans will be chosen under different optimization objectives. Considering economics, the system tends to choose power from CCHP during peak electricity consumption periods and the grid during low electricity consumption periods. Considering energy-saving, ground source heat pumps have advantages over CCHP systems and air source heat pumps.
Increasing the weight coefficient of a certain objective, the optimization results of its corresponding indicators increases, and other indicators may deteriorate. Therefore, in multi-objective optimization, the preference of the decision maker is a key factor that affects the optimization results.

When the weight of a single objective is close to 100%, its marginal effect will decay or even be zero. Reasonable distribution of the weight of multiple objectives can achieve the overall collaborative optimization.

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