ISSN 2004-2965 Energy Proceedings, Vol. 22, 2021

International Conference on Applied Energy 2021
Nov. 29 - Dec. 5, 2021, Thailand/Virtual
Paper ID: 374

A Game Theoretic Perspective on Environment and Economic Operation of Integrated Energy System

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ABSTRACT

Environmental concerns and low-carbon policies have intensified the carbon emission pressure for integrated energy systems (IES) to optimize their operation strategies. To address that, this paper establishes a bi-objective optimization model of integrated energy system operation with the consideration of total operation cost and carbon emission. A Nash-bargain-based approach is employed to determine a compromise solution between two objectives. Results indicate that the proposed approach can make a reasonable tradeoff between the operation cost and carbon emission.

Keywords: integrated energy system, operation optimization, environmental/economic, bi-objective problem, Nash bargain.

1. INTRODUCTION

Under the pressure of global warming, carbon emission reduction has been the international concern [1]. China, with more than 120 countries, has joined the Race to Zero campaign and committed to achieve the zero carbon emissions by 2060 [2]. Zero-carbon solutions have sparked Integrated Energy System (IES) as an entry action. Therefore, the co-realization of the economy and eco-friendliness is the inherent need for IES operation under the carbon emission promise.

The multi-objective optimization problem often serves as a decision-making way for the IES operation. Generally, economy, reliability, environment friendliness, security, etc., are used as the optimization objectives. Mu et al. [3] propose a synergistic strategy for multiple IESs making joint efforts for energy laddering and fulfillment by reusing waste heat. The multi-objective optimization model in [3] achieves a win-win situation for operation economy, environment friendliness, and security. In our previous work [4], a two-stage planning model is proposed to balance the economy and reliability of the integrated energy system.

Game theory, a branch of mathematics, is concerned with the actions of individuals who are conscious that their actions affect each other. It is considered an efficient way to make a tradeoff between the multiple objectives. Wei et al. [5] establish a Nash-bargain and complementarity approach for solving the environmental/economic dispatch problem with DC power flow constraints, but the operation of integrated energy system. Mei et al. [6] contain the uncertainty of energy control, and planning as a typical robust optimization problem. It represents the nature of the zero-sum problem from an engineering perspective of game theory.

This paper establishes a bi-objective model to obtain an optimal operation strategy of the integrated energy system to minimize the total operating cost and CO2 emission. The Nash bargain method is used to determine a compromise solution on the Pareto front of the optimization operation problem between two objectives.

The rest of the paper is organized as follows: Section 2 introduces the integrated energy system; Section 3 establishes the bi-objective model of integrated energy system and uses Nash bargain approach to solve the proposed bi-objective problem. Case studies are performed in Section 4 and conclusions are drawn in Section 5.

Selection and peer-review under responsibility of the scientific committee of the 13th Int. Conf. on Applied Energy (ICAE2021).

2. INTEGRATED ENERGY SYSTEM

As a multi-energy flow energy supply system shown in Fig.1, IES couples cooling, heating, electricity, and other energy sources. IES enables multiple energy to work together, breaking through the blockades under the past independent operation. It is necessary to dispatch the integrated energy system jointly to improve energy utilization efficiency and benefits renewable energy consumption, resulting in lower operating costs and CO2 emission.

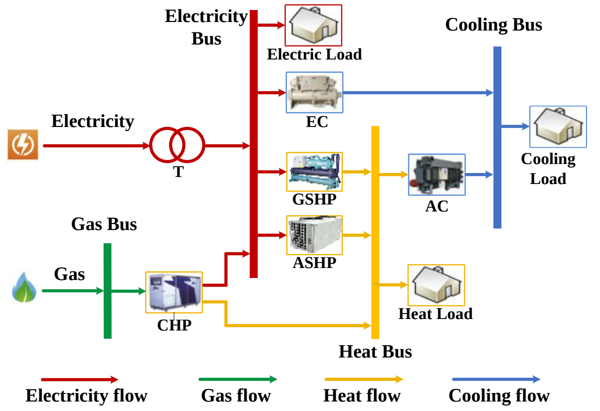

Fig. 1. Structure of integrated energy system

3. THE NASH BARGAIN APPROACH FOR INTEGRATED ENERGY SYSTEM OPERATION

3.1 The bi-objective model of IES operation

In this paper, economy and environmental friendliness are considered as the operation optimization objectives of the integrated energy system, which are measured by the total system operation cost and CO2 emission, respectively. Therefore, the operation model of IES can be formulated as a bi-objective optimization problem as follows.

3.1.1 Economic objective

The economic optimization of IES operation is aimed at the lowest total operating cost during system operation.

$$\min f_C = \sum_d \sum_{t\in T}\left(C_{grid}P_{grid} + C_{gas}P_{gas}\right) \tag{1}$$

where f_C is the annual operation cost of the overall system; d is the typical seasonal day d; the simulation step is 1h and T = 24; P_{grid} and P_{gas} are the purchasing power of electricity and gas; C_{grid} and C_{gas} are the prices of electricity and gas, respectively.

3.1.2 Environmental objective

The environmental friendliness objective of the integrated energy system operation optimization is to minimize the CO2 emission during the system operation.

$$\min f_E = \sum_d D_d \sum_{t\in T}\left(\alpha_{grid}P_{grid} + \alpha_{gas}P_{gas}\right) \tag{2}$$

where f_E is the CO2 emission of the overall system; α_{grid} and α_{gas} are the CO2 emission factors for natural gas combustion and grid purchased electricity, respectively.

3.1.3 Component constraints

As shown in Fig.1, the components of the integrated energy system include transformer (T), combined heat and power (CHP), ground source heat pump (GSHP), air source heat pump (ASHP), electric chiller (EC), and absorption chiller (AC).

$$P_{CHP} = \eta_{CHP} G_{CHP} \tag{3}$$

$$H_{CHP} = v_{CHP} P_{CHP} \tag{4}$$

$$H_{Ashp} = \eta_{Ashp} P_{Ashp} \tag{5}$$

$$H_{Gshp} = \eta_{Gshp} P_{Gshp} \tag{6}$$

$$O_{EC} = \eta_{EC} P_{EC} \tag{7}$$

$$O_{AC} = \eta_{AC} H_{AC} \tag{8}$$

where the subscripts denote the components; P, G, H, and O denote the electricity power, gas input, heating power, and cooling output, respectively; η denotes the efficiency of the component; v_{CHP} is the heat to power ratio of CHP.

$$0 \le P_{CHP} \le C_{CHP} \tag{9}$$

$$0 \le P_{Ashp} \le C_{Ashp} \tag{10}$$

$$0 \le P_{Gshp} \le C_{Gshp} \tag{11}$$

$$0 \le P_{EC} \le C_{EC} \tag{12}$$

$$0 \le H_{AC} \le C_{AC} \tag{13}$$

where C denotes the capacity of components.

3.1.4 Multi energy power balance constraints

$$P_{grid} + P_{CHP} = L_E + P_{Ashp} + P_{Gshp} + P_{EC} \tag{14}$$

$$L_H + H_{AC} = H_{Gshp} + H_{Ashp} + H_{CHP} \tag{15}$$

$$O_{EC} + O_{AC} = L_C \tag{16}$$

$$P_{gas} = G_{CHP} \tag{17}$$

$$0 \le P_{grid} \le P_{grid,\max} \tag{18}$$

$$0 \le P_{gas} \le P_{gas,\max} \tag{19}$$

where L_E, L_H, and L_C are loads of electricity, heat, and cooling; $P_{grid,\max}$ and $P_{gas,\max}$ are the purchasing power bounds of electricity and gas.

Generally, problem (1)-(19) is a bi-objective optimization problem,

$$\begin{gathered} \min \left\{ c_1^{\mathrm{T}} \boldsymbol{x}, c_2^{\mathrm{T}} \boldsymbol{x} \right\} \\ \text{s.t. } \boldsymbol{Gx} \le \boldsymbol{g}, \boldsymbol{Hx} = \boldsymbol{h} \end{gathered} \tag{20}$$

3.2 Nash-bargain-based solution approach

The weighted linear approach is the most popular approach to solve the bi-objective optimization problems,

$$\min\left\{\lambda \boldsymbol{c}_1^{\mathrm{T}}\boldsymbol{x}+\left(1-\lambda\right)\boldsymbol{c}_2^{\mathrm{T}}\boldsymbol{x}\right\} \\ s.t.\ \ \boldsymbol{Gx}\le \boldsymbol{g},\boldsymbol{Hx}=\boldsymbol{h} \tag{21}$$

where λ is the weight, however, it is inevitable that the value of weight is affected by subjectivity.

The two objectives of the problem (20) can be treated as two virtual players who negotiate with each other on how to dispatch components impartially. The optimization goal is to mediate the conflict between two objectives. Therefore, this paper uses the Nash bargain approach [5] to make a reasonable tradeoff between the operation cost and the carbon emission. It has been proved [7] that the bi-objective optimization problem (20) has a bargain solution and satisfies,

$$\max_{x\in \boldsymbol{S}}\left(l_1^m-\boldsymbol{c}_1^{\mathrm{T}}\boldsymbol{x}\right)\left(l_2^m-\boldsymbol{c}_2^{\mathrm{T}}\boldsymbol{x}\right) \tag{22}$$

where set $\boldsymbol{S}$ is the Pareto front of the problem (20); l_1^m and l_2^m are the best unilateral costs.

Next, the problem (22) can render the following problem [5]

$$\begin{aligned} &\max\nolimits_{\boldsymbol{x},\boldsymbol{\eta},\xi,\boldsymbol{z},\lambda}\left(l_1^m-\boldsymbol{c}_1^{\mathrm{T}}\boldsymbol{x}\right)\left(l_2^m-\boldsymbol{c}_2^{\mathrm{T}}\boldsymbol{x}\right)\\ &\lambda\boldsymbol{c}_1+\left(1-\lambda\right)\boldsymbol{c}_2+\boldsymbol{G}^{\mathrm{T}}\boldsymbol{\eta}+\boldsymbol{H}^{\mathrm{T}}\boldsymbol{\xi}=0\\ s.t.\quad &\boldsymbol{Hx}=\boldsymbol{h},\boldsymbol{\xi}\ \text{free}\\ &0\le\boldsymbol{\eta}\le \mathrm{M}(1-\boldsymbol{z})\\ &0\le\boldsymbol{g}-\boldsymbol{Gx}\le \mathrm{M}\boldsymbol{z}\quad \boldsymbol{z}=\left\{z_i\right\},z_i\in\left\{0,1\right\},\forall i \end{aligned} \tag{23}$$

where the weight λ is a decision variable, which can be obtained without subjectivity; $\boldsymbol{\eta}$ and $\boldsymbol{\xi}$ are vectors of dual variables. Then, the optimal solution of problem (23) is the best compromise between two objectives in problem (20).

4. NUMERICAL RESULTS

The proposed Nash bargain model is employed to obtain the optimal operation strategy of the integrated energy system. The structure of the integrated energy system is shown in Fig. 1. The parameters of components are listed in Table I. The electricity, heat, and cooling load curves are shown in [4].

TABLE I
Parameters of Components

Component	Capacity (MW)	η
CHP	100	0.5/0.3 (E/H)
ASHP	12	3
GSHP	14	4.4
EC	90	3.5
AC	60	0.7

The peak electricity price (12-14, 19-22) is 0.18 \$/kWh, the valley price (1-7, 23, 24) is 0.072 \$/kWh and the flat price (8-11, 15-18) is 0.132 \$/kWh. The fixed natural gas price is 0.0392 \$/kWh. The purchasing bounds for electricity and gas are 200MW. The carbon emission factor corresponding to the use of natural gas and electricity consumption are 0.198kg/kWh and 0.137kg/kWh, respectively.

4.1 *Operation optimization*

The optimal operation of the integrated energy system is obtained from the problem (23). The bargain solution and bargain value are marked in Fig. 2 and 3. The problem (21) is solved repeatedly with 1000 uniformly distributed samples of $\lambda \in (0,1)$ to obtain the Pareto front of the bi-objective problem (20) and the objective values of the problem (22). As shown in Fig. 2 and 3, the Nash-bargain-based problem (22) can obtain the best tradeoff between the two objectives in the operation optimization problem (1) - (19).

The results show that the optimal weight parameter λ is 0.7704, the operation cost f_C is 8.4127 × 10^7 CNY, and the carbon emission f_E is 1.6202 × 10^8 kg. It is also observed that cost and CO2 emission are mutually exclusive targets, and the decrease of one side is bound to be accompanied by the increase of the other side. The objective value is close to 0 when the weight parameter λ is less than 0.6, this is because the solution is near to their worst costs in this case.

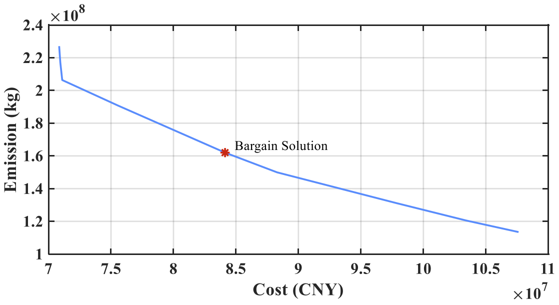

Fig. 2. Pareto front of optimization problem

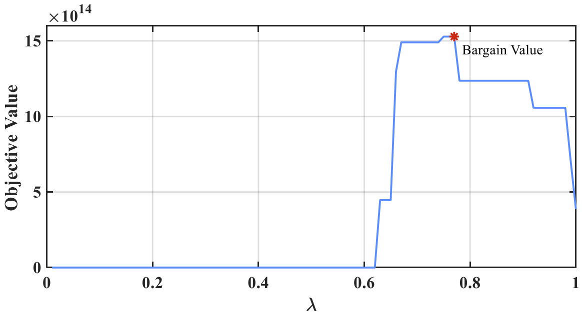

Fig. 3. Bargain solution

4.2 Results on optimal operation strategy

The optimal operation strategies of integrated energy system in spring and winter are shown in Figs. 4 - 7.

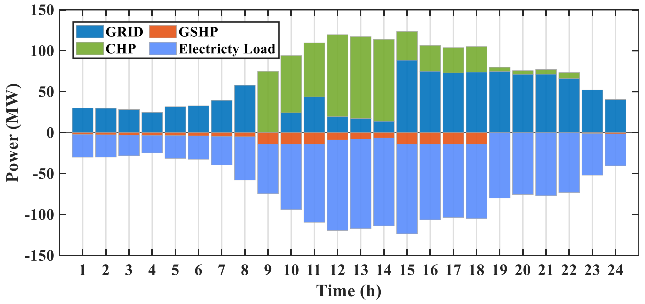

Fig. 4. The optimal electricity operation strategies in spring

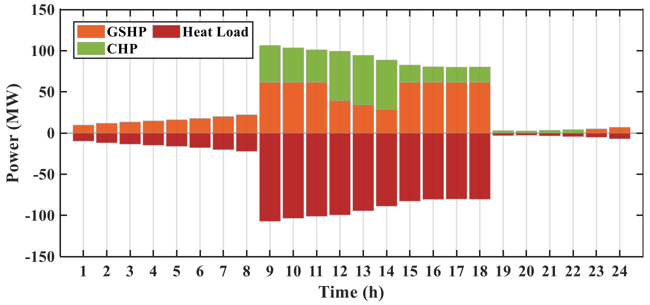

Fig. 5. The optimal heat operation strategies in spring

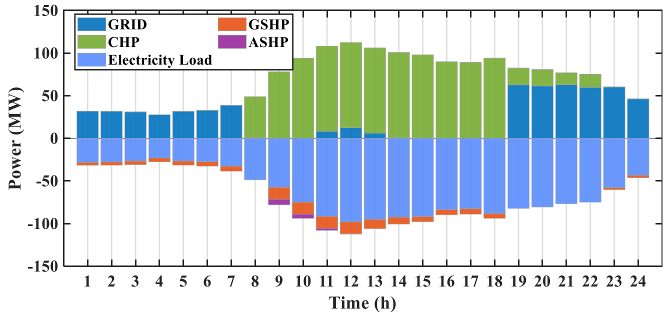

Fig. 6. The optimal electricity operation strategies in winter

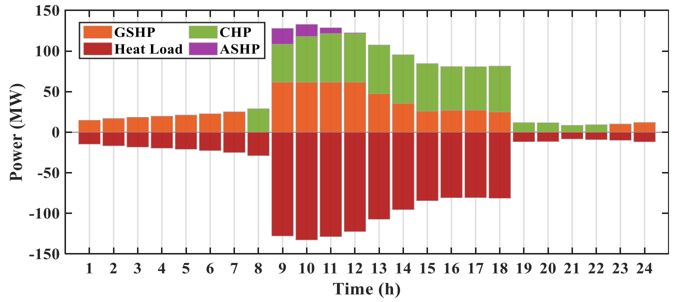

Fig. 7. The optimal heat operation strategies in winter

As shown in Figs, since grid power has lower carbon emission and cheaper price in the peak time, all electricity load is supported by the grid. By contrast, the CHP is the prior component at the other time. Compared with ASHP, GSHP has better performance in the efficiency. Therefore, GSHP also is the main component to supply the heat load, and ASHP is always used to meet the peak load from 9:00 to 11:00 in winter.

5. CONCLUSION

In this paper, an environmental/economic operation optimization model of the integrated energy system is proposed. A Nash-bargain-based approach is adopted to find a compromise operation strategy. The results indicate that the total operating cost and carbon emission of the system can be significantly balanced through the bargaining.

In summary, this paper provides a new way of thinking for the operation of the integrated energy system. However, this study did not consider the planning layout of integrated energy systems, which will be our future research.

ACKNOWLEDGEMENT

This paper is supported by the National Natural Science Foundation of China (U2066211, 52077150).

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