An integrated energy system scheduling optimization method considering economy, stability and environmental protection

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Abstract. In this paper, first, an energy efficiency evaluation method including economy, stability and environmental protection was given. Second, a mathematical model of the integrated energy system and a single-objective economic optimization model under different operation conditions, which add renewable energy and power storage equipment and could be solved based on the greedy algorithm, were given to improve the energy efficiency. Finally, an integrated energy system including wind power, photovoltaics, power storage equipment and conventional loads was taken as an example. Considering the time-of-use electricity price and the full utilization of energy storage, 4 optimization plans were set up for comprehensive energy efficiency evaluation and comparison. The result shows that the energy efficiency evaluation method proposed in this paper is practical and feasible, and the optimization method proposed plays a guiding role in the operation of similar parks.

Keywords. Energy Efficiency Evaluation; Analytic Hierarchy Process; Entropy Weight Method; Day-ahead Optimal Scheduling; Nonlinear programming

1. Preface

The integrated energy system, an important manifestation of the energy Internet, is an integrated system including production, supply and consumption built after rigorous planning and optimization of energy production, transportation, distribution, storage and consumption [1]. The energy efficiency assessment of it is the key to cooperate of various energy systems, optimize the system, and improve energy efficiency. However, there is no silver-bullets until now but only several solutions: The separate energy matrix is used to evaluate the energy saving potentiality of the CCHP system[2]; The evaluation index of the energy system is constructed according to the load curve, cost-efficiency, environment-friendly and other factors, then the information entropy method is used to make the best plan[3]; The modelling optimization and evaluation management of multi-energy systems is analysed, and according to techniques, cost-efficiency, and reliability, the evaluation indicators are proposed in the paper[4].

The cost-efficiency, stability, and environmental protection are the key factors for the long-term and healthy development of the integrated energy system. That’s why this paper selects these factors to evaluate the comprehensive energy efficiency.

The optimization methods of the integrated energy system include single-objective optimization and multi-objective optimization. An efficient and economic day-ahead optimization model is established
in [5]. In [6], a system includes power storage equipment, photovoltaics, gas turbines is analysed. A mixed integer nonlinear programming method is used to calculate to find the lowest operating cost. This paper defines the energy efficiency evaluation indicators and gives method to calculate indicator weights and evaluation scores. And an optimization model is set up, which can be solved by greedy algorithm. Finally, the energy efficiency evaluation results of different scheme are compared, which verifies the effectiveness and guidance of the method proposed in this paper.

2. Energy efficiency evaluation methods and system modeling

2.1. Establishment of energy efficiency evaluation indicators

a. Cost-Efficiency index: The total power supply cost is selected as the cost-efficiency index, and the supply cost calculation formula is:

\[ C = C_s + C_p + C_N + C_C \]  \hspace{1cm} (1)

b. Stability index: The moment when the storage equipment contributes the most to stability is the moment when the energy storage equipment charges and discharges the most power. Therefore, the stability index is defined as the ratio of maximum charge and discharge power of the storage equipment in a cycle to the maximum exchange power between the system and the grid.

c. Environmental protection index: Renewable energy in the integrated energy system is high-valued to environmental protection, so the consumption rate of renewable energy(actual renewable energy generation/caps on renewable energy generation) is selected as a measure.

In this design, there are two kinds of renewable energies: wind and photovoltaic. For wind power generation has a much bigger power than photovoltaic, the consumption rates of them are calculated separately and took in average.

2.2. Index weight calculation and overall score calculation

The weights of the three indexes should be decided first when they are used to evaluate the energy efficiency of the system. Subjective weight calculation method, which will choose the analytic hierarchy process, is suitable to the realistic situation and weights the importance of the three indexes reasonably.

Objective weight calculation method, which will use the entropy method, could avoid subjective arbitrariness, and personal preference will not influence the solution. Two calculation methods are applied both to get the weights of the 3 indexes.

The calculation formula of the comprehensive weight is as follows: (the meaning of the symbols are explained in the appendix)

\[ w^* = \theta w_1 + (1 - \theta) w_2, \theta \in [0,1] \]  \hspace{1cm} (2)

2.3. System modeling method

Under the traditional scheme, there is no battery and renewable energy in the system, and all the power required by the load is purchased from the grid, then there is

\[ P_{\text{fs}} = P_{\text{fr}}, \ P_{\text{f}i} = P_{\text{fi}}, \ P_{\text{s}} = 0 \]  \hspace{1cm} (3)

If all renewable energy is utilized, there is

\[ P_{\text{fs}} = P_{\text{frea}}, \ P_{\text{f}i} = P_{\text{frea}} \]  \hspace{1cm} (4)

If renewable energy is not enough to meet the demand, purchased power from the grid to fill up. Else, surplus energy could be sold to the grid, there is:

\[ P_{\text{fs}} = P_{\text{f}e} - P_{\text{fe}} - P_{\text{f}i}, \ P_{\text{s}} = 0 \]  \hspace{1cm} (5)

Introduce the state variable y to represent the purchased electricity or the sold electricity, y=1 for electricity purchase, otherwise y=0.
There are some strategies can be adopted to reduce power generation costs, we can see it in table 1.

| price comparison | Renewable energy |
|------------------|------------------|
| Power Generation > Purchase | All discarded |
| Power Generation < Sale | All applied |
| Sale < Power Generation | Supply load, no more power |

The single-target optimization model with power storage equipment is:

\[
\begin{align*}
\min C_t &= C_{N4} + C_{\text{ex}} + C_{\text{ex}} + C_{\text{ex}} \\
P_{\text{ex}} + P_{\text{ex}} &= P_{\text{N4}} + P_{\text{N4}} + P_{\text{N4}} \\
C_{\text{N4}} &= \sum_{x=1}^{6} (P_{\text{N4}} w_{x} y - P_{\text{N4}} w_{x} (1 - y)) \\
C_{\text{ex}} &= \sum_{x=1}^{6} P_{\text{ex}} w_{x} \int t \\
C_{\text{ex}} &= \sum_{x=1}^{6} P_{\text{ex}} w_{x} \int t \\
C_{\text{ex}} &= \frac{\sum |P_{\text{ex}}|}{2} \times |t| \times 0.2 \\
|P_{\text{N4}}| &\leq 150 \\
N_{\text{c}} &\leq 8 \\
N_{\text{r}} &\leq 8 \\
|P_{\text{ex}}| &\leq 60 \\
\sum P_{\text{ex}} &= 0 \\
-120 &\leq SP_{\text{ex}} \leq 660 \\
y &= \begin{cases} 0, & P_{\text{N4}} = P_{\text{N4}} - P_{\text{N4}} - P_{\text{ex}} < 0 \\ 1, & P_{\text{N4}} = P_{\text{N4}} - P_{\text{N4}} - P_{\text{ex}} > 0 \end{cases}
\end{align*}
\] (7)

2.4. Greedy algorithm

Greedy algorithm is an algorithm always makes the choice that looks best at the moment when solving a problem, it has a good application in the field of optimal scheduling[7,8,9]. Here are general steps to solve the problem using greedy algorithm: 1. establish the mathematical model of the problem; 2. Divide the problem to be solved into several sub-problems; 3. Solve each sub-problem and obtain the local optimal solution; 4. Combine the local optimal solution into a solution of the original problem. This paper uses the greedy algorithm to solve the nonlinear mathematical model. The optimal solution in each time interval is found and finally synthesized to the total solution.

3. Case analysis

3.1. Introduction of a park system

Taking 15 minutes as a time node, 24 hours can be divided into 96 time nodes. The forecast of load for the next 24 hours is shown in Figure 1, the maximum power of wind in the next 24 hours is shown in
Figure 2, and the maximum power of photovoltaic in the next 24 hours is shown in Figure 3, the 24-hour time-based electricity price table is shown in Table 2.

![Figure 1. Load in 24 hours](image1)

![Figure 2. Maximum power of wind in 24 hours](image2)

![Figure 3. Maximum power of photovoltaic in 24 hours](image3)

**Table 2. Time-based price of electricity**

| time     | 0:00-0:00 | 7:00-0:00 | 10:00-12:00 | 15:00-17:00 | 18:00-19:00 | 21:00-23:00 |
|----------|-----------|-----------|-------------|-------------|-------------|-------------|
| Sale price | 0.21      | 0.41      | 0.64        | 0.41        | 0.64        | 0.41        |
| Purchase price | 0.24      | 0.53      | 0.81        | 0.53        | 0.81        | 0.53        |

3.2. Increase the consumption rate of renewable energy

This plan requires the full use of renewable energy. The formula has been given above, and the optimization results are as figure 4.
3.3. Reduce power supply costs
In this scheme, the cost of power generation is reduced as much as possible to improve the overall energy efficiency of the system. According to the strategies for reducing costs provided above, the optimization results are as figure5.

3.4. Increase the consumption rate of renewable energy and add batteries
Use the greedy algorithm to solve the single-objective optimization model proposed above. The optimization results are as figure6.

3.5. Reduce the cost of power supply and batteries
This scheme uses the single-objective optimization model proposed above while allowing wind and photovoltaic abandonment, so two variables are introduce.

\[
0 \leq P_{s, f} \leq P_{s, \text{max, f}} \\
0 \leq P_{p, f} \leq P_{p, \text{max, f}}
\]  

(8)

The optimization result obtained by using the greedy algorithm is as figure7.

3.6. Score of five schemes

|        | 1  | 2  | 3  | 4  | 5  |
|--------|----|----|----|----|----|
| Economic | 7.574 | 7.574 | 7.574 | 7.574 | 7.574 |
| Stability | 0 | 0 | 0 | 23.23 | 23.23 |
4. Conclusion
In order to improve the energy efficiency of the integrated energy system, a comprehensive energy system energy efficiency assessment method that takes into account economy, stability and environmental protection was proposed in this paper. According to the proposed method, a systematic single-objective economic optimization model was established, and a variety of operation optimization strategies were set based on actual calculation examples to carry out energy efficiency evaluation. Combined with the results of the example, the conclusions are as follows:
(1) If the system does not contain renewable energy and energy storage equipment, then the system has neither environmental protection value nor stable value.
(2) Renewable energy is environmental friendly and guarantees the maximum available energy consumption rate. Therefore, the addition of renewable energy can improve the overall energy efficiency of the system.
(3) If only considering the economic optimum, environmental value cannot be taken into account, which will affect the improvement of the comprehensive energy efficiency of the system. Therefore, it is necessary to combine economic value with environmental value.
(4) The electric storage equipment can not only improve the stability of the system, but also improve the economy of the system. Therefore, the introduction of electric storage equipment can effectively improve the comprehensive energy efficiency of the system.

5. Appendix
C -- the total power supply cost of the system
CS -- the cost of photovoltaic power generation
CF -- the cost of wind power generation
CN -- the cost of power exchange with the grid
CC -- the cost of power storage equipment participating in power supply
w——Comprehensive weight  θ——Preference coefficient
w1——Subjective calculation weight  w2——Objective calculation weight
PNx——Exchange power with the grid in period x (kw)
PLx——Load power in period x (kw)
PFx——Wind power in period x (kw)
PCx——Power of the storage device in the period x (kw)
PSx——Photovoltaic power generation in the period x (kw)

6. References
[1] TAN Zhe, PEI Liang, CHEN Yong, LIU Renliang, “Research on Multi-Source Coordination and Optimization Operation Comprehensive Evaluation Technology for Energy Internet” Electrical and Energy Management Technology, 2019(19):61-68.
[2] KOU Y N, ZHENG J H, LI zhigang. Many-objective optimization for coordinated operation of integrated electricity and gas network[J]. Journal of Modern Power Systems and Clean Energy, 2017, 5(3):350-363.
[3] ZHANG Tao, ZHU Tong, GAO Naiping, WU Zhu, “Optimization Design and Multi-criteria Comprehensive Evaluation Method of Combined Cooling Heating and Power System,” Proceedings of the CSEE, 2015, 35(14): 3706-3713.
[4] LI Yang, WU Ming, ZHOU Haiming, WANG Weiliang, WANG Dan, GE Leijiao, “Study on Some Key Problems Related to Regional Multi Energy System Based on Universal Flow Model,” Power System Technology, 2015, 39(8): 2230-2237.

[5] DUAN Jiangman, WU Yunlai, ZHU Yijie, “The Application of Micro-grid with Multi-energy Complementary in the Design of Intelligent Industrial Park,” SOLAR ENERGY, 2020(04): 71-78.

[6] DONG Fugui, ZHANG Ye, SHANG Meimei, “Multi-criteria Comprehensive Evaluation of Distributed Energy System,” Proceedings of the CSEE, 2015, 35(14): 3706-3713.

[7] Huang Ying-Ying, Pan Quan-Ke, Huang Jiang-Ping, Suganthan PN, Gao Liang. An improved iterated greedy algorithm for the distributed assembly permutation flowshop scheduling problem[J]. Computers & Industrial Engineering, 2021, 152.

[8] Nur Kumala Dewi, Arman Syah Putra. Application of Greedy Algorithm on Traffic Violation Enforcement[J]. International Journal of Education and Management Engineering (IJEME), 2021, 11(1).

[9] Zou Wen Qiang, Pan Quan Ke, Tasgetiren M. Fatih. An effective iterated greedy algorithm for solving a multi-compartment AGV scheduling problem in a matrix manufacturing workshop[J]. Applied Soft Computing, 2020 (prepublish).

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