A rolling prediction optimization strategy for the optimal design of grid connected integrated CCHP system with renewable energy and energy storage

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Abstract. Integrated Combined Cooling Heating and Power (CCHP) system with renewable energy (RE) and energy storage (ES), short as RE-CCHP-ES, is the distributed power station supply electricity, heating, cooling, and hot water by solar, wind power, and natural gas for a specific customer, such as campus, hospital, or commercial palace. Following electric load (FEL) and following the thermal load (FTL) are the traditional operation strategies for CCHP system. But for the system with gas boiler and electricity storage, their performances are not satisfied. Therefore, FLB-RPO operation strategy is designed and contracted with FEL-ECR, and FLB. The result of case study shows that the system designed under FLB-RPO strategy reducing more carbon emission, energy consumption, and system cost than the systems designed under other operation strategy or power supply.

1. Introduction

Building energy demands are divided into electricity, heating, and cooling. Under the traditional power supply (TPS) condition, energy consumption of buildings are mainly on electricity and natural gas, which means all cooling demands are satisfied by electric chiller, and heating demands are mainly satisfied by gas boiler. However, TPS has been widely recognized in high pollution and low efficiency.

RE is the way to reducing fossil fuel consumption and carbon emission. However, volatility of RE could not meet the requirements of power system. Also, CCHP is another way through improving the efficiency of distributed generation by waste heat recovery and energy cascade utilization.

With the developing of ES technology, not only electricity but also hot water and cold water can be storage in tanks as backup power supply. The performance of ES is either damp volatility of renewable generator or balance the difference between supply and demand.

The system integrated CCHP, renewable energy, and energy storage is called RE-CCHP-ES, which is connected in the middle of building energy system and distribution networks.[1,2] This means that multiple requires in design and operation are concerned by multiple participants. Building customer cares about the energy quality as well as the energy price. Investor cares about the capital cost and payback period. Grid network cares about the stability. And the government cares about the carbon emission.

RE-CCHP-ES is playing an important role in the national energy industry, especially for commercial and residential buildings, but it’s the design and operation method facing challenges. This paper focused on the optimal operation strategies for RE-CCHP-ES system design, summarized the latest researches, and put forward an optimal structure and operation strategy.
2. Literature review

2.1. System structure
For CCHP system, power generation unit (PGU) and absorption chiller (AC) is indispensable. RE-CCHP-ES is upgraded from CCHP system, which is the distributed power station supply electricity, heating, cooling, and hot water by solar, wind power, and natural gas generators for a specific customer, such as campus, hospital, or commercial palace. As shown in the Figure 1, the units of RE-CCHP-ES system is divided in to four categories, including source, generator, storage & conversion, and customer load from the left to the right respectively.

![Figure 1. Units of RE-CCHP-ES system.](image)

There are two main features of RE-CCHP-ES, one is multi-energy sources, which means that different kinds of distributed power generator capacitated in the system are cooperated together. Another is multi-power supply, which mean that system satisfied electrical demands, heating demands, and cooling demands at the same time.

With RE generation integrated into the system, the system is faced with the fluctuation of randomness and intermittence from renewable energy and the customer load at the same time. For the two random fluctuations that system faces, it could be simplified into one by total consumption of RE power generation. Then, through the control of ES, the difference between the customer loads with the outputs of main units is further eliminated.

However, in some structures design of integrated CCHP, the regulating function of ES has not been fully realized. Electric battery and thermal storage are all passively added in to the system and configured the capacity.

2.2. Operation strategies
FEL and FTL is the traditional CCHP operation strategy. However, the performance of FEL or FTL is not efficiency enough with high cooling demands. Divided cooling demands into electrical chiller demands and absorption chiller demands by electric cooling ratio (ECR) is the common solution [3]. Moreover, following a hybrid electric-thermal load (FHL) strategy tried to avoid wasting electricity and thermal energy, and following the seasonal operation (FSS) strategy and following the electric-thermal load of buildings (FLB) is aimed at investigate the system performance in monthly and hourly by the rate of electrical load to thermal load (LR) [4]. Overall, FEL-ECR and FLB has better performance than others [3, 4]. Characteristics of these operation strategies are summarized in the Table 1.
Table 1. The characteristics of CCHP system operation strategies.

| Strategy | Description |
|----------|-------------|
| FEL[5]   | The power of PGU follows electrical demands. The corresponding heat is supplied to the thermal demand. And the extra thermal demands are satisfied by gas boiler. The power of PGU follows thermal demands. The corresponding electricity is supplied to the electrical demand. And the extra electrical demands are satisfied by power grid. |
| FTL[5]   | Cooling demand is divided by ECR, electrical demands and electrical chiller demands have a higher priority than the thermal demand and absorption chiller demands, and the extra thermal demands are satisfied gas boiler. Cooling demand is divided by ECR, thermal demands and absorption chiller demands, and the extra electrical demands are satisfied by power grid. |
| FEL-ECR[1] | According to the ratio of monthly electric load to thermal load, the power of PGU is operated under FTL or FEL. |
| FTL-ECR[1] | According to the ratio of hourly electric load to thermal load, the power of PGU is operated under FTL or FEL. |
| FSS[4]   | According to the ratio of monthly electric load to thermal load, the power of PGU is operated under FTL or FEL. |
| FLB[4]   | According to the ratio of hourly electric load to thermal load, the power of PGU is operated under FTL or FEL. |

However, all the strategies above are not considering the prediction and the daily energy balance of generation and load. With the renewable energy units and energy storage units integrated into CCHP system, peak cut shifting at both ends of generation and load becomes a new way to improve system efficiency and stability. Passive energy storage and non-predictive operation strategies have not been able to meet this demand [6].

2.3. Performance evaluation

Common evaluation objectives for CCHP systems are mainly focus on profit and emission. Profit index is mainly energy cost saving relative to TPS and payback period of the system capital cost. Emission index is mainly carbon dioxide reduction relative to TPS. But this cannot respect all the design requirements.

R. Jing et al. put forward the energetic assessment to representing the efficiency of CCHP system and indicating the match between system capacity and energy demand [7]. K. Yang et al. divided 12 indexes into two level layers, the attribute layer including technology, economic, environment, and societal index [8]. G. Li et al. calculated the probability of failing to satisfy the electrical demand and the thermal demand, which is defined as loss of energy supply probability [5].

Various and meticulous evaluation objectives make better guidance to the system design optimization. Therefore, stability, efficiency, economic, and emission are chosen in this study for optimal design and result comparison.

This study based on the previous researches of integrated CCHP system structures, operation strategies, and evaluation targets proposing the typical structure of RE-CCHP-ES system, and following the load of building with rolling prediction optimization (FLB-RPO) operation strategy. System and model framework is described in section 3. A case study is analyzed in section 4. And the conclusions are summarized in the last section.

3. Model framework

To maximum the advantages of RE-CCHP-ES system, we designed the FLB-RPO operation strategy for not only traditional CCHP system but also various integrated CCHP system. In addition to high efficiency, reduction of cost, and emissions optimization objectives, stability is the compulsory condition in this design. Assumptions, methodology and functions are elaborated below.
3.1. System structure

In order to maximize the peak load regulation function of energy storage, we designed a typical RE-CCHP-ES system that connected with the electric grid, and the structure is shown in the Figure 2. And there are some points should be clear here:

(1) The system is mainly driven by solar, wind, and natural gas, and the electric grid play as backup when meeting system failure or peak demand.

(2) The ES components are the balance controller which collecting electric or thermal from the generators and distribute to the conversion and customer load.

(3) The electrical chiller or HVAC system of the customer has enough capacity to supply the cooling demands after absorption chiller.

(4) Due to renewable generator should installed as much as possible, so the capacity optimization includes PGU, AC, gas boiler (GB), electric battery (EB), and thermal storage (TS).

3.2. Methodology description

The scenario assumptions and boundaries of FLB is consistent with FEL and FTL. Customer loads and RE generation is forecasted and calculated by customer loads data and renewable energy sources data. For customer loads data, electric data is mainly from lighting, instruments, devices, and equipment loads, and heating and cooling data are from HVAC system that stabilize indoor temperature. And renewable energy sources data come from monitoring instruments. In the result, FLB-RPO strategy gives the power of main units hourly based on the 24 hours prediction of RE generation and customer loads.

Figure 2. Structure of the typical RE-CCHP-ES system. Figure 3. FLB-RPO operation strategy.
3.2.1. FLB-RPO operation strategy

FLB-RPO operation strategy is based on FLB and covered by RPO, which is shown in Figure 3. The FLB operation strategy is shown in the yellow box. As RE and ES is not involve in the former study, we have made some improvements to adapt to RE-CCHP-ES system structure. For a specific time state from annual 8760 hours round, FLB could balance the power of each unit to improve the performance of the overall system by two parameters, ECR and LR. The specific steps are as follows:

Step 1: Checking EB and TS state of the previous hour, and predicting the RE generation RE and customer loads, EL, CL, and HL.

Step 2: Decreasing EL by RE generation first. And then increasing EL and HL by ECR and CL, and the power of AC is obtained incidentally. The function as following:

\[ a_c = f(AC_{\text{max}}, 1 - ecr \times cl, AC_{\text{min}}) \]  
\[ e_l = e_l + \frac{cl - ac}{COP_{ec}} \]  
\[ h_l = h_l + \frac{ac}{COP_{ac}} \]

Where \( AC_{\text{max}} \) is the capacity of AC, \( AC_{\text{min}} \) is the minimum power of AC, and \( COP_{ec} \) and \( COP_{ac} \) are the COP of electrical chiller and absorption chiller, respectively.

Step 3: If the rate of EL and EB to HL and TS is less than LR, the system runs in FTL strategy. Otherwise, the system runs in FEL strategy.

Step 4: EL and HL is satisfied by the system and power grid with excess energy stored, and the powers of each unit are obtained.

The rolling prediction optimization (RPO) is shown in the blue box of Figure 3. For a specific hourly of the year, RPO calculated the powers of each main unit of the next 24 hours by FLB strategy. Then through three time scale data to keep the power fluctuating of PGU, GB, and AC smoothly. The specific steps are as follows:

Step 1: Input a specific hour with the state of EB and TS.

Step 2: Predicting the power states of each unit by FLB operation from the current hour to the next 23 hours independently.

Step 3: Combining the result of step 2 into three time scale, and optimizing the current power states of PGU. The optimization function as following:

\[ p_{gu_i} = f\left(p_{gu_i}, \frac{\sum_3^3 p_{gu_i}}{3}, \frac{\sum_1^{24} p_{gu_i}}{24}\right) \]  

Where \( p_{gu_i} \) is the power state of PGU in each hour.

Step 4: Calculating the current power states of GB, AC, EC, ES, TS, and GE based on the result from step 3 through FLB strategy.

3.3. Component formulation

For PV panel, micro wind turbine, PGU, gas boiler, absorption chiller, electric chiller, electric battery and thermal storage, whole working condition model can be referred to the power curve given by the manufacturer. Formulation models and constraint s are summarized in the Figure 4 and Table 2.
Figure 4. Power curve lines of steady state model under full working condition.

| Item               | Constraint                                    | Efficiency range         | High performance interval          |
|--------------------|-----------------------------------------------|--------------------------|------------------------------------|
| PV panel           | Solar irradiance >100W/m²                     | -                        | Solar irradiance >350W/m²          |
| Micro wind turbine | Wind speed >1.5m/s                            | -                        | Wind speed >4m/s                   |
| PGU                | Power >20%                                    | Electrical efficiency:   | Power >60%, electrical efficiency >0.26 |
|                    |                                               | [0.11,0.36]              |                                    |
|                    |                                               | Thermal efficiency:      | Power >50%, efficiency >0.90      |
|                    |                                               | [0.42,0.56]              |                                    |
| Gas boiler         | Power >20%                                    | Thermal efficiency:      | Power >50%, efficiency >0.90      |
|                    |                                               | [0.86,0.96]              |                                    |
| Absorption chiller | Power >20%                                    | COP: [0.41,1.35]         | Power >65%, COP >1.00             |
| Electric chiller   |                                               |                          |                                    |
| Electric battery   | Charging and discharging process: 50%/h      | Charging and discharging | SOC >15%                           |
|                    |                                               | efficiency: 95%          |                                    |
| Thermal storage    | Temperature <90°C                             | Energy loss: 5%/h        |                                    |

3.4. Performance evaluation

As stability is the compulsory requirement of system design, which means the capacity could fully meet the cooling/heating load anytime around the year without failures. Therefore, the performance evaluation has three objectives, including economic, efficiency, and emission.

3.4.1. Economic objective. Economic objective is the function of capital cost, and operation cost.

\[
esco = \sum_{i=1}^{8760} gas_i \cdot price_{gas} + \sum_{i=1}^{8760} grid_i \cdot price_{grid} + \frac{\sum_{i} \text{unit}_i \cdot price_i}{20} \tag{5}
\]

Where \(esco\) is the annual cost in RMB, \(gas\) is the annual natural gas consumption in m³, \(price_{gas}\) is the unit price of natural gas in RMB/m³, \(grid\) is the electricity import form power grid in kWh, \(price_{grid}\) is the unit price of grid electricity in RMB/kWh, and \(unit\) and \(price\) is the capacity of main unit in kW and corresponding capital cost in RMB/kW, respectively.
3.4.2. Efficiency objective. Efficiency objective is the function of annual energy supply and annual gas and power input.

$$\text{eff} = \frac{\sum_{i=1}^{8760} (\text{load}_i^e + \text{load}_i^h + \text{load}_i^{ac})}{\sum_{i=1}^{8760} (\text{gas}_i \cdot cv_{gas} + \frac{\text{grid}_i}{\text{eff}_{grid}})}$$  \hspace{1cm} (6)

Where $\text{eff}$ is the system annual energy efficiency in percentage, $\text{load}_i^e$, $\text{load}_i^h$, and $\text{load}_i^{ac}$ is the customer electrical, customer heating, and AC loads in kWh, $cv_{gas}$ is the calorific value of natural gas in kWh/m$^3$, $\text{grid}_i$ is the electricity import form power grid in kWh, and $\text{eff}_{grid}$ is the efficiency factor of grid power.

3.4.3. Emission objective

Emission objective is the weight of the carbon exhaust from natural gas and power grid.

$$\text{emi} = \sum_{i=1}^{8760} \text{gas}_i \cdot \text{carb}_{gas} + \sum_{i=1}^{8760} \text{grid}_i \cdot \text{carb}_{grid}$$  \hspace{1cm} (7)

Where $\text{emi}$ is the annual CO$_2$ emission in kg, $\text{carb}_{gas}$ is the carbon emission coefficient of natural gas in kg/m$^3$, and $\text{carb}_{grid}$ is the carbon emission coefficient of grid electricity in kg/kWh.

4. Case study

Checking the feasibility and performance of FLB-RPO operation strategy, we take traditional power supply mode as baseline and contract with FEL-ECR and FLB operation strategy in the all year round simulation. System capacities and evaluation objectives are optimized in four kinds of operation strategies.

4.1. A subsection

A typical commercial building with electric, space heating/cooling demands located at Jinan, where winter is from December to March, summer is June to September, and take February 1st and August 1st as typical days. The renewable energy resources are shown in the Figure 5, and customer load is shown in the Figure 6.

![Figure 5. Solar and wind energy located at the typical customer site.](image)

![Figure 6. Annual energy demand of the typical customer.](image)
For renewable energy generations, there are 300 m² roof area available, and 6 sits for 1kW micro wind turbine. After analyzing optimum dip angle by latitude and longitude, the PV panel capacity is 25 kW, and the micro wind turbine capacity is 6 kW.

4.2. Algorithms and constraints

The optimal design algorithm in this study is Non-dominated Sorting Genetic Algorithm III (NSGA-III) Copyright (c) 2016 Yarpiz (www.yarpiz.com), by Matlab software vision R2014a. NSGA-III settings, unit price, and energy factors are shown in Table 3.

Table 3. Optimal design settings of NSGA-III.

| Item                  | Component        | Value           |
|-----------------------|------------------|-----------------|
| NSGA-III Setting      | Optimization item| PGU, GB, AC, EB, TS, ECR, LR |
|                       | Population size  | 30              |
|                       | Crossover fraction| 0.8             |
|                       | Mutation Percentage| 0.8          |
|                       | Mutation rate    | 0.1             |
|                       | Generations      | 100             |
| Unit price            | PV               | 7000 RMB/kW     |
|                       | Micro wind turbine| 6000 RMB/kW   |
|                       | PGU              | 4000 RMB/kW     |
|                       | GB               | 850 RMB/kW      |
|                       | AC               | 2200 RMB/kW     |
|                       | EB               | 3200 RMB/kWh    |
|                       | TS               | 250 RMB/kWh     |
|                       | Purchase price   | 1.00 RMB/kWh    |
|                       | Sale price       | 0.40 RMB/kWh    |
|                       | Emission factor  | 0.785 kg/kWh    |
|                       | Efficiency       | 0.35            |
|                       | Price            | 2.4 RMB/m³      |
| Grid electricity      | Emission factor  | 2.16 kg/m³      |
|                       | Calorific value  | 10 kWh/m³       |

4.3. Result analysis

All objectives performance (OP) in different type of power supply modes or operation strategies are contrast in the Figure 7. The best capacity design is obtained from 30 solutions of each operation strategy. The performance evaluations are the shown in Table 4.

Figure 7. Optimal design result by NSGA-III.
Table 4. Capacities and objectives of annual performance evaluation.

| Strategy | Capacity (kW) | Parameter | Emission (10 t) | Efficiency (%) | Economic (10,000 RMB) |
|----------|--------------|-----------|----------------|----------------|-----------------------|
|           | PGU | GB  | AC  | EB  | TS | ECR | LR |           |
| TPS      | -   | 199 | -   | -   | -  | -   | 67.54 | 42.75 | 85.75 |
| FEL-ECR  | 69  | 124 | 152 | 0   | 41 | 0   | 47.34 | 57.40 | 60.04 |
| FLB      | 76  | 120 | 82  | 0   | 117| 0   | 44.49 | 57.53 | 53.47 |
| FLB-RPO  | 85  | 106 | 87  | 0   | 99 | 0.65| 42.99 | 58.07 | 49.04 |

From the design result of units capacity and evaluations, RE-CCHP-ES system makes significant reduction of emission, energy consumption, and system cost under FLB-RPO operation strategy, which makes better performance than FEL-ECR and FLB. However, EB capacity in all operation strategies are 0, which is mainly due to the highly capital cost.

5. Conclusions
This study focused on the optimal design of RE-CCHP-ES system, FLB-RPO operation strategy gives priority to the use of waste heat for cooling load, and predicting and actively storing energy for peak cutting and valley filling. Through the short-term and long-term prediction, the power of PGU is optimized by active energy storage operation to maintain efficient operation. The result of case study shows that the system designed under FLB-RPO strategy reducing more carbon emission, energy consumption, and system cost than the systems designed under other operation strategy or power supply.

To the further study, more kinds of customer could be analyzed to checking the performance of FLB-RPO strategy. Also the multiple time scale rolling prediction optimization could be designed to separate the electric response out, which would provide more specific analysis for PGU and ES performance.

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