Multi-objective optimal operation of renewable energy hybrid CCHP system using SSO

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Abstract. In recent years, the amalgamation of renewable energies into combined cooling, heating and power system (CCHP) become a popular research in energy field. In order to improve the energy utilization of renewable energies integrated the CCHP (RECCHP) system, it is necessary to optimize the operation and component capacity in the RECCHP system. A multi-objective optimization model characterizing the system daily operation cost, daily carbon dioxide emission, and primary energy saving rate is established. Considering each objective function, Simplified Swarm Optimization (SSO) is applied as a single objective optimization problem to find the best capacity of components and operation of the system. Further, normalize three objective respectively and use Analytic Hierarchy Process to get weight for each objective. Transform the multi-objective optimization problem into a single objective optimization problem. Finally, taking a historical weather data in winter of Kinmen Island, Taiwan, as a case study, solve the problem with SSO, and the experiment results are compared with traditional energy systems. The results show that the RECCHP system is better than traditional energy systems among economic, environmental and energy aspect.

1. Introduction

During the recent decade, demand of energy increase rapidly, causing intensified emission of Carbon dioxide and lead to troubling environmental issues. Hence, global awareness of environmental protection rises and energy shortage becomes more serious. Therefore, the combined cooling, heating and power (CCHP) microgrid has received escalating attention since it has high efficiency in the energy utilization, and also, it has been regarded as an essential technology to manage distributed energy and mitigate environmental pollution. The CCHP microgrid integrates distributed energies, components of CCHP system and energy storage devices, which can select grid-connected operation or isolation operation, enhancing efficiency, economy and reliability performance of energy system [1]. The structure, components capacity and energy output schedule of the CCHP microgrid are determined to lead the environment protection and economy performance to achieve optimal, considering the electric, thermal and cooling demand. The early researches of the CCHP microgrid optimization almost focus on the minimization of system cost cause of expensive devices of the CCHP microgrid [2]. In recent years, in addition to system cost, researchers have started to take system reliability and environmental sustainability into account,
optimizing the energy management, component capacity and energy generation scheduling [3]. In the development of the CCHP system, there are two major approaches in the literature to optimize the CCHP system, component size and optimal operation for energy management respectively. For instance of component size, Akbari et al. [4] concerned about designing energy system of building by means of robust optimization, constrained by uncertainties of demand, costs and prices. Sayyaadi and Abdollahi [5] presented a multi-objective model for capacity of the CCHP system based on the exergetic efficiency, total levelized cost rate and the cost rate of environmental. For another aspect, some studies researched optimal operation and energy management of the CCHP system. For example, Liu et al. [6] analyzed the hourly operation combined with ground source heat pump under different loads. Chen et al. [7] considered the performance of the residential CCHP incorporated with fuel cell and solar technologies.

At present, more researchers study the hybrid CCHP system based on renewable energies. Soheyli et al. [8] built a novel CCHP system coupled with renewable energies (RECCHP) and applied the co-constrained multi-objective particle swarm optimization (CO-MOPSO) to optimize. Kang et al. [9] inspected the energy and environmental potential of a RECCHP system, taking into consideration of Korea and Canada weather conditions.

Above all, many researches in the relative literature have investigated the optimization of CCHP, but few of them inspected the multi-objective optimization of the RECCHP system, and also, most of papers studied the optimization of the CCHP system using the load data of a hypothesis building, that is to say, few papers focused on how to optimize the CCHP system in particular district using actually historical weather and loading condition as the input data. In this paper, coincidently, Taiwan government has implemented the “Low-Carbon-Emission in Kinmen Island Policy” these years. This policy aims to reduce carbon emission in electric generated procedure by setting renewable energies and electric storage device. Therefore, it is potential for Kinmen Island promoting the RECCHP system so that we take the daily operation cost, the carbon dioxide emission and primary energy rate as the objectives, considering the energy balance constraints. Then, adopt the Analytic Hierarchy Process to transform the multi-objective optimization problem into the single objective. Eventually, apply simplified swarm optimization to solve the problem. Compare the optimal results with each objective functions and discuss.

2. CCHP model

2.1. Structure of RECCHP

Figure 1 shows the energy flow of recommended RECCHP system, including the renewable energies, solar cell (PV) and wind turbine (WT) respectively, and devices of the CCHP system, containing micro gas turbine (GT), gas boiler (GB), electric storage device (ES), thermal storage devices (HS), electric chiller (EC) and absorption chiller (AC).

![Figure 1. Energy flow chart of CCHP microgrid.](image)
2.2. Objective function
The objectives of the RECCHP model are minimizing the daily operation cost, minimizing the daily carbon emission and maximizing the primary energy rate which are $F_1$, $F_2$ and $F_3$ respectively.

\[
f = \min \{ F_1, F_2, F_3 \} \tag{1}
\]

2.2.1. Daily operation cost
\[
F_1 = \sum_{t=1}^{T}(F_{\text{NG}}(t)+F_{\text{OM}}(t)+F_{\text{Grid}}(t)) \tag{2}
\]
\[
F_{\text{NG}} = F_{\text{GT}}(t)+F_{\text{GB}}(t) \tag{3}
\]
\[
F_{\text{OM}}(t) = \sum_{i=1}^{M}K_{\text{OM},i}P_i(t) \tag{4}
\]
\[
F_{\text{Grid}}(t) = -J_{\text{Grid}}(t)+P_{\text{Grid}}(t) \tag{5}
\]

Where $F_{\text{NG}}$ and $F_{\text{OM}}$ are respectively the fuel cost and management cost of devices. $F_{\text{GT}}$ and $F_{\text{GB}}$ are respectively the fuel cost of GT and GB. $K_{\text{OM},i}$ is the management cost of device $i$ generating per unit energy. $P_i$ is the output energy of device $i$. $J_{\text{Grid}}$ is electricity price. $P_{\text{Grid}}$ is the exchanged electricity energy between power grid and microgrid.

2.2.2. Carbon dioxide emission
\[
F_2 = \sum_{t=1}^{T}(P_{\text{Grid}}(t)u_{\text{Grid}}+(F_{\text{NG}}(t)u_{\text{NG}})/\text{Price}_{\text{NG}})) \tag{6}
\]

Where $u_{\text{Grid}}$ is the amount of carbon dioxide emission when power grid generate per unit electricity power. $u_{\text{NG}}$ is the amount of carbon dioxide emission when per unit of natural gas is burned. $\text{Price}_{\text{NG}}$ is the per unit price of natural gas.

2.2.3. Primary energy rate
\[
F_3 = (\sum_{t=1}^{T}R_{\text{out}}(t))/\sum_{t=1}^{T}R_{\text{in}}(t) \tag{7}
\]
\[
R_{\text{out}}(t) = Q_{\text{load}}(t)+P_{\text{load}}(t)+C_{\text{load}}(t) \tag{8}
\]
\[
R_{\text{in}}(t) = P_{\text{PV}}(t)+P_{\text{WT}}(t)+(P_{\text{GT}}(t)\eta_{\text{GT}})+(Q_{\text{GB}}(t)\eta_{\text{GB}})+(P_{\text{Gridbuy}}(t)/\eta_{\text{Grid}}) \tag{9}
\]

Where $R_{\text{out}}$ and $R_{\text{in}}$ are the output energy and the input energy of microgrid, respectively. $Q_{\text{load}}, P_{\text{load}}$ and $C_{\text{load}}$ are thermal load, electricity load and cooling load, respectively. $P_{\text{PV}}, P_{\text{WT}}$, $Q_{\text{GB}}$ and $P_{\text{GT}}$ are respectively output of PV, WT, GB and GT. $\eta_{\text{GT}}, \eta_{\text{GB}}$ and $\eta_{\text{Grid}}$ are efficiency of GT, GB and power grid, respectively.

2.3. Constraints
2.3.1. Energy balance
\[
P_{\text{PV}}(t)+P_{\text{WT}}(t)+P_{\text{GT}}(t)+P_{\text{Grid}}(t)+P_{\text{ES},\text{d}}(t)=P_{\text{ES},\text{a}}(t)+P_{\text{EC}}(t)+P_{\text{load}}(t) \tag{10}
\]
\[
Q_{\text{rec}}(t)+Q_{\text{GB}}(t)+Q_{\text{HS},\text{d}}(t)=Q_{\text{HS},\text{a}}(t)+Q_{\text{AC}}(t)+Q_{\text{load}}(t) \tag{11}
\]
\[
C_{\text{AC}}(t)+C_{\text{EC}}(t)=C_{\text{load}}(t) \tag{12}
\]

Where $Q_{\text{AC}}$ and $C_{\text{AC}}$ are input and output of AC, respectively. $P_{\text{EC}}$ and $C_{\text{EC}}$ are input and output of EC, respectively. $Q_{\text{rec}}$ is recycle thermal energy from GT.
2.3.2. Storage constraints

\[ E_{ES}(t+1) = E_{ES}(t) + P_{ES,c}(t) \eta_{ES,c} - P_{ES,d}(t) \eta_{ES,d} \]  \hspace{1cm} (13)

\[ 0 \leq P_{ES,c}(t) \leq V_{ES} \gamma_{ES,c} \]  \hspace{1cm} (14)

\[ 0 \leq P_{ES,d}(t) \leq V_{ES} \gamma_{ES,d} \]  \hspace{1cm} (15)

\[ P_{ES,d}(t) P_{ES,c}(t) = 0 \]  \hspace{1cm} (16)

Where \( E_{ES} \) is the stored energy of ES. \( P_{ES,c} \) and \( P_{ES,d} \) are respectively the charging power and discharging power of ES. \( \eta_{ES,c} \) and \( \eta_{ES,d} \) are respectively the charging efficiency and discharging efficiency of ES. \( V_{ES} \) is the size of ES. \( \gamma_{ES,c} \) and \( \gamma_{ES,d} \) are charging rate and discharging rate of ES, respectively.

3. Method

3.1. Single objective optimization

In this paper, the proposed Simplified swarm optimization (SSO) is adopted. It was originally introduced by Yeh in 2009 [10]. The parameters of the proposed algorithm are simple and flexible. Moreover, the global search capability of SSO is excellent. The update mechanism of SSO is shown below.

\[ x_{ij}^{t+1} = \begin{cases} g_j & \text{if } \rho \in [0, C_g) \\ p_{i,j} & \text{if } \rho \in [C_g, C_p) \\ x_{ij}^t & \text{if } \rho \in [C_p, C_w) \\ x & \text{if } \rho \in [C_w, 1] \end{cases} \]  \hspace{1cm} (17)

Where \( x_{ij}^{t+1} \) is the particle \( j \) in solution \( i \) when generation is \( t+1 \). \( g_j \) is the global best value of particle \( j \). \( p_{i,j} \) is the the best value of particle \( j \) in solution \( i \). \( x \) is the random value between upper bound and lower bound of particle \( i \). \( \rho \) is the random number between 0 and 1.

3.2. Analytic Hierarchy Process

Analytic Hierarchy Process (AHP) belongs to the multi-criteria decision making methods. For multi-objective optimization or multi-criteria decision problem, AHP can transform a complex problem into a simple hierarchy construct by collecting opinions from experts. Then, translate the subjective opinions into measurable numeric relations and derive the pairwise comparison matrix. Calculate the eigen value from the matrix to evaluate the strongness of relationship of criterias. In this paper, use the overall weights from relevant literature [11] which are adopted by AHP. The transformed single objective function is shown as below.

\[ f = \min \left( w_1 \frac{F_1 - F_{1,\text{min}}}{F_{1,\text{max}} - F_{1,\text{min}}} + w_2 \frac{F_2 - F_{2,\text{min}}}{F_{2,\text{max}} - F_{2,\text{min}}} + w_3 \frac{F_3 - F_{3,\text{min}}}{F_{3,\text{max}} - F_{3,\text{min}}} \right) \]  \hspace{1cm} (18)

3.3. Case study

In this paper, the case study of the RECCHP system in Xi Kou village, Kinmen, Taiwan is selected since our study not only optimize the RECCHP system but also yearn for promoting the CCHP technologies in Taiwan. The input data, output energy of photovoltaic generation, output energy of wind turbine, electricity load, thermal load and cooling are simulated from historical winter weather condition in Kinmen.

3.3.1. Photovoltaic generation
\[ P_{PV} = P_{STC} G_{AC} \frac{1 + \omega (T_c - T_{STC})}{G_{STC}} \]  

(19)

Where \( P_{PV} \) is the output energy of solar cell. \( P_{STC}, T_{STC} \) and \( G_{STC} \) is the maximum output of solar cell, irradiance and temperature under standard test condition, respectively. \( \omega \) is temperature coefficient of output. \( T_c \) is the actual working temperature.

3.3.2. Wind turbine

\[
P_{WT}(v) = \begin{cases} 
P_t \frac{v - v_e}{v_r - v_e} & (v_e \leq v \leq v_r) \\
P_t & (v_r \leq v \leq v_f) \\
0 & (v \leq v_c \text{ or } v \geq v_f)
\end{cases}
\]  

(20)

Where \( P_{WT} \) is the output energy of wind turbine. \( P_t \) is maximum output energy. \( v_e \) is cut-in wind speed. \( v_r \) is effective wind speed. \( v_f \) is cut-off wind speed. \( v \) is the actual wind speed.

3.3.3. Parameters

In this paper, the compositions of the RECCHP system can be described as follows: PV with the peak capacity of 150kW, WT with the peak capacity of 50kW, and the capacity of other devices are not limited since this study aims to find the most suitable capacity and optimal operation of all components in the RECCHP system for selected district. The time-of-use electricity price is 3.33 NTD from 7 to 22 and the other time is 1.39 NTD. PV and WT output energy are shown in figure 2. Electricity load, thermal load and cooling load are shown in figure 3. Table 1 shows the parameters of all devices [12].

![Output of renewable energies](image1)

**Figure 2.** Hourly output of PV and WT.

![Demand of loadings](image2)

**Figure 3.** Hourly loading.
**Table 1.** Parameters of devices.

| parameters    | value  | parameters | value |
|---------------|--------|------------|-------|
| $K_{OM,GT}$ (NTD/kWh) | 0.1805 | $\eta_{HS,c}$ | 0.98  |
| $K_{OM,GB}$ (NTD/kWh) | 0.0459 | $\eta_{HS,d}$ | 0.98  |
| $K_{OM,WT}$ (NTD/kWh) | 0.1332 | $\sigma_{ES}$ | 0.02  |
| $K_{OM,PV}$ (NTD/kWh) | 0.0432 | $\sigma_{HS}$ | 0.04  |
| $u_{Grid}$ (kg/kWh) | 0.637  | COP$_{AC}$ | 1.38  |
| $u_{NG}$ (kg/m³) | 2.09   | COP$_{Ec}$ | 3  |
| $Price_{NG}$ (NTD/m³) | 12.96  | $\gamma_{ES,c}$ | 0.2  |
| $\eta_{GT}$ | 0.45   | $\gamma_{ES,d}$ | 0.4  |
| $\eta_{GB}$ | 0.89   | $\gamma_{HS,c}$ | 0.2  |
| $\eta_{ES,c}$ | 0.95   | $\gamma_{HS,d}$ | 0.4  |
| $\eta_{ES,d}$ | 0.95   | $\eta_{Grid}$ | 0.4  |

**4. Results and discussion**

**4.1 Optimization results**
To improve the quality of solution and make the optimized results more suitable with actual condition in Kinmen, there are two rules for optimization process. Rule1: Never sell the electricity energy to power grid. Rule2: The output of GT must satisfy at least 60% of electricity load after PV, WT and ES output being reduced from original electricity load since the development of the CCHP is far from maturity in Kinmen. Thus, we should try the best to make the electricity generation self-sufficient firstly.

At first, SSO is applied to solve optimization problem for each single objective, $F_1$, $F_2$ and $F_3$. The parameters of SSO, $C_p$, $C_p$, $C_w$, $N_{gen}$ and $N_{sol}$ are 0.4, 0.75, 0.9, 200 and 150, respectively. Afterwards, transform the multi-objective optimization problem into the single objective problem by equation (18). Figure 4 and figure 5 respectively show the optimal dispatch results of the electricity energy and thermal energy for $F_1$. To observe easily, the charging energy of ES and HS are placed in the area of negative axis. Figure 6 and figure 7 show the optimal dispatch results of the electricity energy and thermal energy for $F_2$, respectively. The results of $F_3$ are similar to $F_2$, thus the figures are not shown below. Figure 8 and figure 9 respectively show the optimal dispatch results of the electricity energy and thermal energy for $f$. Moreover, the optimal results for each objective functions are show in Table.2.
Figure 4. The optimal dispatch result of electricity energy of $F_1$.

Figure 5. The optimal dispatch result of thermal energy of $F_1$.

Figure 6. The optimal dispatch result of electricity energy of $F_2$. 
Figure 7. The optimal dispatch result of thermal energy of $F_2$.

Figure 8. The optimal dispatch result of electricity energy of $f$.

Figure 9. The optimal dispatch result of thermal energy of $f$.

Table 2. Parameters of devices.

| Objective Function | Daily operation cost (NTD) | Carbon dioxide emission (kg) | Primary energy rate(%) |
|--------------------|-----------------------------|-----------------------------|------------------------|
| Traditional        | 15009.01                    | 3081.38                     | 45.60%                 |
| $F_1$              | 11795.95                    | 2089.44                     | 70.17%                 |
| $F_2$              | 11940.82                    | 2057.17                     | 73.15%                 |
| $F_3$              | 11962.06                    | 2060.11                     | 73.41%                 |
| $f$                | 11901.43                    | 2067.29                     | 71.96%                 |
4.2 Results discussion
As shown in figure 4 and figure 5, the RECCHP system purchases a large amount of electricity energy from power grid between time 0 and time 6, indicating that the operation cost of the RECCHP system by purchasing electricity energy is lower than the operation cost of the RECCHP system by GT generating electricity energy when the time-of-use electricity price is in valley. Also, since the storage energy of ES is zero, ES keep charging plenty of electricity between time 0 and time 2. Moreover, the output electricity of GT almost satisfy the total electricity load, that is to say, because the thermal load in winter day is high, generating electricity energy by GT can recycle the thermal power. Hence, it can reduce operation cost of whole system. For thermal load, GB generates plenty of thermal energy between time 0 and time 8, indicating that the thermal load is much more than electricity load so that GT can not make full use of its advantage. Besides, the electricity load is more than thermal load at time 8. HS almost keep charging between time 10 and time 20. After time 21, owing to thermal load increasing, HS discharge to reduce the operation cost.

In figure 6 and figure 7, the RECCHP system purchases little electricity energy from power grid and GT almost satisfy the electricity demand whole the day, suggesting that the amount of carbon emission of GT running is lower than the amount of carbon emission of purchasing electricity energy from power grid. In addition, the optimal dispatch result of F3 is similar to F2 in that the trade-off between minimizing carbon dioxide emission and maximizing the primary energy rate is not strong. As shown in figure 8 and figure 9, the RECCHP system scarcely purchase the electricity energy from power grid to reduce carbon dioxide emission and primary energy rate, revealing that the overall weights adopted from recommended paper for $F_1$, $F_2$ and $F_3$ are 0.2725, 0.3529 and 0.3745, respectively. Therefore, the optimal dispatch result for $f$ is more similar to $F_2$ and $F_3$. Table.2 shows the optimal values for each objective optimization. For each objective optimization, the optimal solution is much better than traditional energy systems. What’s more, compared with single objective optimization, the multi-objective optimization reach the balance among operation cost, carbon dioxide emission and primary energy rate. Nevertheless, for all objectives, $F_1$, $F_2$, $F_3$ and $f$, the difference of optimal solution is not obvious. The probably reason is that Kinmen Island is located in subtropical monsoon climate zone, that is, there is not pretty cold in winter. Hence, the electricity load is more than thermal load by daylight so the advantage of GT can not be made full use.

5. Conclusion and future work
In this paper, a multi-objective optimal operation of the RECCHP system is constructed, taking the daily operation cost, daily carbon emission and primary energy rate as the objectives, considering the constraints of energy balances and energy storage. Get the overall weight for each objective by AHP from relevant literature. Then, transform the multi-objective optimization problem into the single objective optimization problem by normalizing. To solve the objective optimization, the SSO algorithm is proposed. Taking the winter day in Kinmen as the input data, solve the optimization problem and obtain the optimal dispatch result. The results show that the RECCHP system performs well, compared with traditional energy systems. The multi-objective optimization can achieve a comprehensive among the operation cost, carbon dioxide emission and primary energy rate. For future works, it should be more careful for input data. In the RECCHP system, the input data concern the algorithm procedure and final result very much. Furthermore, construct the different operation strategy for the different problem. The suitable strategy not merely make the optimization problem easier but also improve the quality of solution.

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