Optimization of the Configuration of the CCHP System

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Abstract. In this article, we have optimized the total operational cost of combined cooling heating and power system (CCHP). This cost is further divided into three major parts, which are the capital cost of the equipment, fuel cost, and the grid electricity cost. The heat storage tank has also been used to store the excessive heat that can be utilized when needed. A genetic algorithm has been used for the optimization of the whole system. The decision variables chosen were 74. The optimization resulted in significant reduction in the total cost. The final results show that the cooling demand was significantly supplied by the Grid through the electric chillers because of higher coefficient of performance, while the power demand was met through the power generation unit. Results shows that the natural gas cost consumption is much greater then the grid and equipment cost.

1. Introduction

Today’s conventional grid is based on outdated technologies where the systems are unable to withstand the growing demand caused by modern development and increased population. This causes a lot of problems like power outages, lack of reliability, technical and non-technical losses, consumer dissatisfaction, environmental issues, etc. To overcome all these issues, CCHP also known as combined cooling heating and power systems are developing rapidly these days [1].

CCHP is a tri-generation system that can produce cooling, heating, and electricity at the same time. This system is usually placed closed to the on-site that makes it very efficient as the transmission and distribution losses are greatly reduced. This will also reduce greenhouse gas emissions which makes it more environmentally friendly. Another huge benefit of this system is that it can store the excessive heat produced by the power generation plants that can be used later for heating and cooling purpose which will further improve the system efficiency [2].

Some major components of CCHP system are the power generation unit (PGU) which is used to provide the required electricity for the buildings, heat recovery unit that can be used to recover the waste heat from the PGU, absorption chiller that will use the waste recovered heat to meet the cooling demand, and the heat exchanger that uses the same recovered heat for heating purpose. Other than that electric chiller can also be used to provide cooling using electricity and boiler to provide the required heat to the heat exchanger depends on the system requirement [3].

In past most of the work was performed on CHP system also known as combined heating and power like in [4], author optimizes CHP without considering the cooling unit also in [5,6] author considers the cooling unit as well but did not consider the heat storage unit so the additional heat will be wasted. In [7] the author considers multiple heat exchangers and did excellent work but in this work, the additional electricity from the PGU cannot be sold back to the grid. Such limitations can decrease the overall efficiency of the CCHP system.
Different optimization can be used to optimize the CCHP system. In this research work, a genetic algorithm (GA) is used. The reason for choosing this algorithm is that it supports multiple objectives and works in parallel which saves time and it usually provides better results than most of the other algorithms. The author in [8] uses GA effectively for the CCHP optimization problem also in [9] and [10] author did an excellent job in optimizing the objective function use GA. Block diagram of the CCHP system is mentioned in the figure 1 below:

![Figure 1. CCHP system Block Diagram](image)

In this research it is possible to sell the electricity back to the grid when the demand is less than the generation, also heat can be stored using a heat storage unit and that can be utilized during peak hours. Time of use pricing scheme will be used where tariff will be changed according to the load demand which makes it more flexible.

2. Research objective
The major goal of this research work is to optimize the overall operational cost of the system using the genetic algorithm. For this purpose some rules need to be followed:

Excess heat from the PGU that will be recovered by the heat recovery unit will be used first to provide to the absorption chiller for cooling or heat exchanger for heating purpose. If the recovered heat is more than heating and cooling demand, then the additional heat can be stored in the heat storage tank.

If recovered heat is insufficient, then the heat storage tank will be used to fulfil the heating and cooling demand respectively if it’s capable. If not, then the remaining heat will be provided by the boiler. The boiler will not be used to provide any heat to the heat storage tank. If the absorption chiller is not enough to provide the required cooling then electric chiller will be used that will operate on electricity taken by power generation unit or from the grid when needed. The surplus electricity can be sold back to the grid if the electricity produced by the PGU is more than the demand.

3. Objective function
To optimize the overall operational cost of the CCHP system represented by $C_{CCHP}$, our research objective is divided into three major parts which are the sum of the total capital cost of the equipment's ($C_{eq, cap}$), natural gas cost ($C_{ng}$) and the grid electricity cost ($C_{grid}$) as mentioned in equation 1.

$$C_{CCHP} = C_{eq, cap} + C_{ng} + C_{grid}$$  \hspace{1cm} (1)

Now in equation (1),

$$C_{eq, cap} = \sum_i(A_i \cdot C_{eq,i} \cdot G_i)$$  \hspace{1cm} (2)
Where $A_i$ is the capital recovery factor of equipment index $i$ and in this research work, seven different equipment are used so the value of $i$ would be seven in this research work.

In equation (2), $CC_{eq,i}$ is the Unit capital cost of each equipment and $G_i$ is the rated capacity of each equipment.

Now, the value of $\sum_i CC_{eq,i} * G_i$ for all the equipment will be:

$$\sum_i CC_{eq,i} * G_i = \sum_i ((CC_{PGU} * G_{PGU}) + (CC_{HRSO} * G_{HRSO}) + (CC_{ac} * G_{ac}) + (CC_{ec} * G_{ec}) + (CC_{boiler} * G_{boiler}) + (CC_{sto} * G_{sto}) + (CC_{he} * G_{he}) )Y/kW * kW$$

Where, $CC_{PGU} , CC_{HRSO} , CC_{ac} , CC_{ec} , CC_{boiler} , CC_{sto} , CC_{he}$ are the per-unit cost of PGU, heat recovery unit, absorption chiller, electric chiller, boiler, heat storage tank, and heat exchanger respectively. Their values are mentioned in table 2 and after putting all these values in equation 2, we will get:

$$C_{eq, cap} = A_i \sum_i ((6800 * G_{PGU}, HRSO) + (1200 * G_{ac}) + (970 * G_{ec}) + (300 * G_{boiler}) + (230 * G_{sto}) + (200 * G_{he})) Y/kW * kW$$

(3)

In equation (1),

$$C_{ng} = \sum_i \sum_t CC_{ng} * F_{it,t}$$

or

$$C_{ng} = CC_{ng} \sum_t \sum_i F_{it,t}$$

(4)

Here, $C_{ng}$ is the natural gas cost, $CC_{ng} = 0.2235 Y/kWh$ which is the unit price of natural gas from table 4. $F_{it,t}$ is the sum of natural gas consumption by the PGU and boiler together for each hour $t$ which works as a fuel that can be represented as:

$$\sum_t \sum_i F_{it,t} = \sum_t F_{pgu,t} + \sum_t F_{boiler,t}$$

(5)

Where,

$$F_{pgu,t} = E_{pgu,t} / \eta_{pgu,t}$$

(6)

And

$$F_{boiler,t} = Q_{boiler,t} / \eta_{boiler,t}$$

(7)

In equation 6, $F_{pgu,t}$ is the amount of fuel required to operate the PGU, $E_{pgu,t}$ is the electricity production by the pgu and $\eta_{pgu}$ is the PGU efficiency whereas in equation 7, $F_{boiler,t}$ is the amount of fuel required to operate the boiler, $Q_{boiler,t}$ is the amount of heat produced by the boiler which also equals to the sum of boiler heat for the heat exchanger and boiler heat for the absorption chiller represented by $Q_{phe,t}$ and $Q_{bac,t}$ respectively. Also, $\eta_{boiler}$ is the boiler efficiency respectively. Put equation (6) and (7) in equation (5) we will get,

$$\sum_t \sum_i F_{it,t} = \sum_t \left[ \left( \frac{E_{pgu,t}}{\eta_{pgu,t}} \right) + \left( \frac{Q_{boiler,t}}{\eta_{boiler,t}} \right) \right]$$

(8)

Now put equation (8) in equation (4) we will get:

$$C_{ng} = 0.2235 \sum_t \sum_i F_{it,t}$$

$$= 0.2235 \left( \sum_t \left( \frac{E_{pgu,t}}{0.3} \right) + \left( \frac{Q_{boiler,t}}{0.85} \right) \right)$$

(9)

In equation (1), $C_{grid}$ which is the total grid cost is:

$$C_{grid} = \sum_i CC_{grid,t} * E_{grid,t} - \sum_t CC_{grids,t} * E_{grids,t}$$

(10)
Where $CC_{grid,t}$ and $CC_{gridst,t}$ are the costs of buying and selling electricity from the grid, $E_{gridb,t}$ and $E_{gridst,t}$ are the amount of electricity that we are buying and selling to the grid.

$$E_{gridb,t} = \begin{cases} 0 & \forall \text{Load}_{electricity,t} + E_{ec,t} \leq E_{pgu,t} \\ \text{Load}_{electricity,t} + E_{ec,t} - E_{pgu,t} & \text{Otherwise} \end{cases}$$

Where

$$E_{gridst,t} = \begin{cases} 0 & \forall \text{Load}_{electricity,t} + E_{ec,t} \geq E_{pgu,t} \\ E_{pgu,t} - \text{Load}_{electricity,t} + E_{ec,t} & \text{Otherwise} \end{cases}$$

Putting equation (3), (9) and (10) in (1) we will get,

$$C_{CCHP} = C_{eq, cap} + C_{ng} + C_{grid}$$

$$C_{CCHP} = A_i \sum_i (6800 * G_{PGU, HRSG} + (1200 * G_{ac}) + (970 * G_{ec}) + (300 * G_{boiler}) + (230 * G_{sto}) + (200 * G_{ne})Y/KW*KW + 0.2235 \sum_i (\frac{E_{pgu}}{0.85} + (\frac{Q_{boiler}}{0.95})) + \sum_i CC_{gridb,t} \cdot E_{gridb,t} - \sum_i CC_{gridst,t} \cdot E_{gridst,t}$$

(11)

Where

$$A_i = \frac{r \cdot (1 + r)^{Year_i}}{(1 + r)^{Year_i} - 1}$$

$r$ is the interest rate which is 4.9%, $Year_i$ represents equipment lifetime of index i which is 10 years in this research work. So after calculating, $A_i = 0.1289$ for each equipment index $i$.

Also, there are some energy balance equations and constraints that need to be followed

$$E_{pgu,t} + E_{gridb,t} - E_{gridst,t} = \text{Load}_{electricity,t} + E_{ec,t}$$

(12)

$$Q_{rec,t} + Q_{boiler,t} = Q_{rac,t} + Q_{rhe,t} + Q_{bact} + Q_{bheat} + E_{tsto,t}$$

(13)

$$E_{ssto,t} \leq E_{scap}$$

(14)

The amount of heat recovered by the heat recovery unit from the PGU is:

$$Q_{rec,t} = (F_{pgu,t} - E_{pgu,t}) \cdot \eta_{rec}$$

or

$$Q_{rec,t} = F_{pgu,t} \cdot \eta_{rec}(1 - \eta_{pgu})$$

Also

$$Q_{rec,t} = Q_{rac,t} + Q_{rhe,t}$$

Where $Q_{rec,t}$ is the recovered heat for heating load, $Q_{boiler,t}$ is the boiler heat, $Q_{rac,t}$ is the recovered heat required by absorption chiller for cooling. $Q_{rhe,t}$ is the recovered heat for heat exchanger, $\eta_{rec}$ is the efficiency of heat recovery unit. The amount of heat provided by the boiler for heating purpose will be:

$$Q_{boiler,t} = Q_{bact} + Q_{bheat}$$

(15)

Where $Q_{bact}$ is the boiler heat required by absorption chiller, $Q_{bheat}$ is the boiler heat needed for heat exchanger.

Only heat recovery unit will be used to store the heat. Total cooling load will be provided by the combination of electric and absorption chiller such that:

$$Q_{act} + Q_{ec,t} = \text{Load}_{cooling,t}$$

$$Q_{act} = x \cdot (Q_{act} + Q_{ec,t})$$
\[ Q_{ec,t} = E_{ec,t} \cdot \text{COP}_{ec} = \text{Load}_{cooling,t} - Q_{ac,t} \]

Where \( Q_{ac,t} \) the amount of cooling that is generated from the absorption chiller, \( Q_{ec,t} \) is the amount of cooling generated from the electric chiller and \( x \) is the cooling ratio which describes below:

\[ x = \frac{Q_{ac,t}}{Q_{ac,t} + Q_{ec,t}} \]

Input recovered and boiler heat required for the absorption chiller to meet the cooling demand is:

\[ Q_{ract} + Q_{bac,t} = \frac{Q_{ac,t}}{\text{COP}_{ac,t}} \]

The heating load should be equal to the sum of recovered heat for the heat exchanger, boiler heat for heat exchanger, and heat provided by the heat storage tank when needed.

\[ \text{Load}_{heating,t} = (Q_{rhe,t} + Q_{bhe,t} + E_{tsto,t}) \cdot \eta_h \]

Where \( E_{tsto,t} \) the input or output of the heat storage tank is, \( E_{sto,t} \) is the energy stored in the storage tank, \( E_{cap} \) is the heat storage tank capacity that would be calculated by the genetic algorithm.

The value of \( E_{tsto,t} \) is positive when it stores the excess heat and negative when it is used to provide the required heat.

Some inequality constraints that are used in this research are as follow:

- \( E_{cap} \leq [0,5000] \)
- \( E_{pgu,t} \leq E_{cap} \)
- \( E_{sto,t} \leq E_{cap} \)
- \( E_{stcap} \leq [0, 2000] \)
- \( x \leq 1 \)

There are a total of 74 constraints that are needed to be tackled. 1 is for the PGU capacity \( E_{cap} \) and heat storage \( E_{stcap} \) each, then 24 PGU values \( E_{pgu,t}, \) and heat storage values \( E_{sto,t} \) that should always be less than their respective capacities and then the 24 values for the cooling ratio \( x \). The decided value for \( E_{cap} \) is based on the maximum load of electricity, heating, and cooling while keeping in mind the selling of electricity and heat storage units. The power generated from the PGU \( E_{pgu,t} \) should be less or equals to the power generation unit capacity load \( E_{cap} \). The value heat storage capacity \( E_{stcap} \) depends on the maximum value of heating and cooling demand.

The genetic algorithm is based on Charles Darwin's theory of natural evolution where the algorithm creates a random initial population and the fittest individuals from them are selected as parents. The fittest individuals are carefully chosen for the reproduction process to produce offspring for the next generation. Those offspring have better qualities from their parents. This process keeps on repeating until the fittest generation is not found.

The reason for choosing this algorithm is that it supports multiple objectives and works in parallel which saves time and it usually provides better results than most of the other algorithms.

4. Results discussions

GA parameters, components cost, Performance parameters, energy price, and used in this research are mentioned in tables 1, 2, 3, and 4 respectively. The load demand profile that is used in this research is mentioned in Figure 2. These values are taken from [11,12], and [13] respectively. In figure 3, the capacities of each equipment depend on their capital cost values, that's why the capacity of PGU is minimum as its capital cost is maximum, and increasing the capacity of PGU will also increase the overall operational cost of the CCHP system which is not feasible. Also, the capital cost of the absorption
chiller is more than the cost of electric chiller and there is a major difference between the values of their COP as well.

Table 1. Parameters for GA.

| Parameter       | Value |
|-----------------|-------|
| Population Size | 100   |
| Crossover       | 0.8   |
| Mutation        | 0.01  |
| Elite Count     | 2     |
| Scaling Function| Rank  |
| Selection Function| Roulette |

Table 2. Cost of the components

| Equipment                          | Unit Capital Cost(Y/KW) |
|------------------------------------|-------------------------|
| PGU and Heat Recovery              | 6800                    |
| Absorption Chiller                 | 1200                    |
| Electric Chiller                   | 970                     |
| Boiler                             | 300                     |
| Heat Storage Tank                  | 230                     |
| Heat Exchanger                     | 200                     |

Table 3. Performance Parameters

| Parameter                                      | Symbol  | Value |
|-----------------------------------------------|---------|-------|
| Coefficient of performance of absorption chiller | COPacs  | 0.7   |
| Coefficient of performance of electric chiller  | COPecs  | 3.5   |
| PGU efficiency                                | ηrec    | 0.3   |
| Heat recovery system efficiency                | ηrec    | 0.8   |
| Boiler efficiency                              | ηboiler | 0.85  |
| Heat exchanger efficiency                      | ηh      | 0.8   |
| Heat storage tank thermal efficiency           | ηsto    | 0.9   |
| Equipment’s Life                               | Year    | 10    |

Table 4. Energy price of CCHP system

| Parameter                  | Unit    | Value   | Comments             |
|---------------------------|---------|---------|----------------------|
| Unit price of electricity  | Y/Kwh   | 0.852   | 0.426                |
|                           |         | 1.278   | 0:00 – 5:00, 23:00 – 24:00, 6:00 – 8:00, 12:00 – 17:00, 9:00 – 11:00, 18:00 – 22:00 |
| Unit price of natural gas  | Y/Kwh   | 0.2235  | Feed-in tariff       |
|                           |         | 0.3749  | /                    |

The capital cost of the boiler is just 300 yuan/Kw and also its efficiency is 0.8 as compared to the PGU efficiency which is just 0.3 so using a boiler is a better option in this case. As we are using the heat
recovery unit and boiler to provide the required heat for cooling and heat so that why the capacity of heat storage unit is very small as a small amount of additional heat is getting stored in the heat storage tank and will be utilized later when needed. The value of the heat exchanger depends on the total heating load as this unit will provide all the required heating demand.

**Figure 2. Load profile**

**Figure 3. Equipment Capacities**

**Figure 4. Cost Comparison**
In figure 3, the capacities of each equipment depend on their capital cost values, that's why the capacity of PGU is minimum as its capital cost is maximum, and increasing the capacity of PGU will also increase the overall operational cost of the CCHP system which is not feasible. Also, the capital cost of the absorption chiller is more than the cost of electric chiller and there is a major difference between the values of their COP as well. The capital cost of the boiler is just 300 yuan/Kw and also its efficiency is 0.8 as compared to the PGU efficiency which is just 0.3 so using a boiler is a better option in this case. As we are using the heat recovery unit and boiler to provide the required heat for cooling and heat so that why the capacity of heat storage unit is very small as a small amount of additional heat is getting stored in the heat storage tank and will be utilized later when needed. The value of the heat exchanger depends on the total heating load as this unit will provide all the required heating demand.

Figure 4, shows the cost comparison where it can be seen that the capital cost of equipment is the lowest and as the equipment capacities are quite small then we are taking most of the electricity from the grid to fulfill the electricity as well as cooling demand provided by the electric chiller.

Also, the natural gas cost value is more as fuel will be used for PGU and boiler both.

Figure 5, shows the comparison between the cooling produced by the electric chiller to the absorption chiller. As the PGU capacity is low due to its high capital cost, the heat recovery unit will be able to capture the very small amount of heat to provide it to the absorption chiller to fulfill the cooling demand. That’s why most of the time electric chiller will be used to provide the required cooling. Another reason is the difference between their Coefficients of performance (COP), which is only 0.7 for the absorption chiller and 3.5 for the electric chiller.

As compared to the heating and cooling demand, electricity demand is quite low in most of the hours that can be seen in fi and due to its high capital cost as discussed before, the capacity of PGU is quite
low so to fulfill the remaining load, buying electricity from the grid is compulsory. The electricity load profile from both the PGU and grid can be seen in figure 6.

5. Conclusion
This research work focuses on the optimization of the overall operational cost of the CCHP system. For this purpose, a genetic algorithm is used. It can be seen that to reduce the overall operational cost, the cost of equipment is minimum which will also impact the grid and natural gas cost.

The capacity of the PGU is quite low due to its high capital cost, that why buying electricity from the grid is compulsory to meet the electricity demand.

Also, due to this reason, the heat recovery unit is not able to capture the required amount to meet the heating and cooling demand. So, a boiler and electric chiller will be used to fulfill these demands when needed.

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