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# Optimum sizing and tracking of combined cooling heating and power systems for bulk energy consumers

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## HIGHLIGHTS

- The capacity optimization reduces the optimum annual energy cost of combined cooling, heating and power systems.
- The deterministic solution to the optimum operation strategy reduces the inaccuracies and the computation down time.
- The graphical user interface used in system operation increases the practical applicability of the methodology.
- The proposed methodology has reduced the total annual cost over 13% compared to the thermal load following mode.

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## ABSTRACT

The optimization of combined cooling heating and power (CCHP) systems involves two major tasks: searching for optimum design parameters and for optimum regular operation variables. This paper proposes a two-stage method to solve both tasks. The operation of large thermal power plants must be altered smoothly, as quick changes in system settings may result in cascade tripping of subsystems, ultimately leading to a complete shutdown. This work uses graphical representation of the operational space of the system, which helps in tracking the operation along its optimum trajectory smoothly. The daily energy demands of a five star hotel, collected over a year, were used to demonstrate the applicability of the proposed method. Using the proposed method reduced the total annual cost over 7% and 13% in Australia and Sri Lanka respectively, compared to the conventional method of following thermal load.



## 1. Introduction

Concerns about climate change and our dependence on ever-depleting fossil fuel reserves has turned scientific research towards the enhancement of conversion efficiencies of both conventional and renewable energy technologies. The conventional centralized power generation from fossil fuel is less productive, as waste heat or steam cannot be economically transmitted. The generation of electricity with decentralized power generation technology helps in utilizing waste heat where electricity or fuel would otherwise have been used.

Combined cooling heating and power (CCHP) systems utilize energy sources effectively by cascading cooling and heating systems along the descending temperature of waste heat streams. This introduces an additional constraint of the relative dependency of each energy commodity. But the demands of these three energy commodities are mutually exclusive and stochastic. This mismatch between demand and supply reduce the productivity of the generation process. Thorough analysis is needed to improve the productivity due to the higher degree of freedom in operation. Following electricity or thermal demand is the convenient and conventional operation strategy used in the literature, but a hybrid strategy that maximizes or minimizes different objectives would be more appropriate in highly volatile energy markets.

The synthesis of optimization of combined cooling heating and power systems implies searching for design and operation parameters that minimize or maximize an objective function, such as annual economic cost, environmental load or thermodynamic efficiency under a given set of constraints. In this study we mainly focus on the minimization of total annual cost while optimizing the system capacity and the regular operation. In fact, the optimization of the system capacity is a two-stage optimization problem, with two different set of variables pertaining to system's capacities and operation parameters. Most of the studies in the literature formulated the problem into a single objective function searching for optimum design parameters together with fixed operating indices that remained unchanged. Several studies have focused only on the

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**Nomenclature**

| | | | |
|---|---|---|---|
| $C$ | design capacity (kW) | $ac$ | absorption cooling |
| $COP$ | coefficient of performance | $elc$ | electric cooling |
| $D$ | demand | $nc$ | natural cooling |
| $DD$ | daily demand | $avg$ | average |
| $E$ | electricity (kW) | $gen$ | generator |
| $F$ | fuel (l) | $rcy$ | recovery |
| $H$ | heat (kW) | $blr$ | boiler |
| $N$ | unit cost ($) | $grd$ | grid |
| $P$ | operating capacity (kW) | | |
| | | *Greek letters* | |
| *Subscripts* | | $\alpha$ | grid electricity share |
| $c$ | cooling | $\beta$ | electric cooling share |
| $e$ | electricity | $\eta$ | efficiency |
| $h$ | heating | | |

optimum operation and successfully determined the optimum operating point, but the methodology that changes the current operating settings into the optimal is unclear [1,2]. Large power plants cannot usually respond to a quick transition from their current operating point to an optimal operating point found using optimization techniques. The result may be a cascade tripping of each subsystem, leading to a complete shutdown of the plant.

### 1.1. Contribution

We introduce a two-stage optimization algorithm that searches for optimal system capacities while optimizing the regular operation. Furthermore, this maps the objective function onto a three-dimensional space, making it possible to track the plant smoothly along the optimum operation trajectory using a graphical user interface. This includes the part load performance of the subsystems, enhancing the accuracy and practical applicability of the methodology.

### 1.2. Outline of the paper

This paper presents a methodology that optimizes the capacity and regular operation of CCHP systems. Section 2 presents an overview of the literature, with a brief introduction to the proposed method and its importance. Section 3 describes the proposed methodology and modeling of the system physics in three-dimensional space. Section 4 describes the case study: an application of the methodology to a real world hotel. Section 5 gives the results and discussion of the case study. The article concludes with a brief summary.

## 2. Related work and proposed improvements

### 2.1. Previous work

Numerous methodologies are adopted in the literature, of which the following is a selective taxonomy.

The expected goals from a CCHP system are highly dependent upon the system sizing and designing, and proper matching of the demand and the supply. Many of the works in the literature are based on optimization search algorithms. Operations cost, $CO_2$ emission, and primary energy consumption [1,3–14] are some of the objective functions used in the optimization algorithms. However, the prime purpose of these works is to propose a methodology that optimizes the capacity and the regular operation of the CCHP systems. Therefore, here we consider only the capacity and operation cost optimization algorithms proposed in the literature.

Mago [15] used different objective functions to compare the CCHP operating strategies of following thermal load (FTL), electric load (FEL) and a hybrid strategy by switching the plant between FTL and FEL, no specific optimization algorithm was used. Lozano [16] used a linear programming model to determine the appropriate mode of operation from among three types of modes that minimize the operation cost in a volatile energy market. Arcuri [17] and Lozano [18] used mixed integer linear programming (MILP) for optimal design using hourly energy demand over a year, but the operation cost for a given hour may not be optimal. Similar approaches were introduced by Wang [19,20] and Tichi [21] using genetic and particle swarm algorithms respectively to determine the optimum capacity. Cho [22] introduced dynamic programming method to optimize operation cost switching the plant between FTL and FEL. Kavvadias [23] introduced five operation strategies including FTL and FEL, compares them and selects the best. Chicco [24] introduced a matrix model that determines the minimum operation cost of CCHP systems with a given set of sub system capacities. The sequential quadratic programming method was used to determine the optimum operating loads of each sub-system to minimize the operating cost. Ooka [25] determined the optimum capacities and electric cooling to total cooling ratio that minimized total annual cost but the operating cost may not always be optimal. Kong [26] introduced a parametric analysis for a set of one-dimensional independent variables against gas engine sizes and electricity to gas cost price ratio. The optimum values were used to determine the minimum primary energy cost. Abdollai [27] proposed a multi criterion decision making algorithm including risk analysis. The monthly energy demand of an end user is used in decision making, together with a search algorithm to determine the optimum energy dispatch of the micro-turbine and absorption chiller. A similar method was proposed by Sayyaadi [28] for sizing of a residential small-scale CCHP systems. Fang [29] added an organic Rankine cycle to the conventional CCHP system. The relative performance was compared with a CCHP without electric chillers. Four different operation strategies of CCHP-ORC were evaluated using two independent variables (electric chiller and ORC energy dispatch factors) under dynamic demand and finally the best strategy was selected. Jabbari [30] determined the optimum configuration out of two CCHP systems configurations proposed using genetic algorithm. Liu [31] determined the maximum hourly cost saving between two system configurations with unlimited generator capacity and optimum generator capacity. The energy dispatch ratio of electric cooling to cooling demand is considered as the only decision variable in optimization.