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An Innovative Design and Cost Optimization of a Trigeneration (Combined Cooling, Heating and Power) System

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ABSTRACT: Load management and cost optimization are among the important factors in trigeneration systems and combined cooling, heating and power (CCHP) systems. In this study, an innovative CCHP system uses a gas turbine as the prime mover and has a heat recovery steam generator (HRSG) in addition to an auxiliary boiler, electric and absorption chillers. The system is tied with the bulk electric grid; to export and sell excess power or import power when necessary. This study analyzes load management and cost optimization of CCHP systems. A heuristic strategy to optimize the total energy cost is then presented. The optimal size of CCHP is determined from the study results. This paper proposes a model for CCHP system optimization based on minimization of energy consumption and initial investment costs. It is to be noted that the selected variables are the size of the gas turbine, the absorption chiller capacity, and other dependent components.

Key words: Modeling, Optimization, Energy, CCHP

INTRODUCTION

CCHP systems use waste heat created as a byproduct of power generation to accomplish required heating or cooling demand (Bhatt, 2001; Wang *et al.*, 2002). With the availability of gas turbines to span an increasingly wide range of capacities, it is becoming more attractive to utilize a CCHP via a combination of gas turbines and absorption chillers. CCHP systems, can be used at industrial plants, hospitals, hotels, or business centers to satisfy electric, heating, and cooling demands from a single energy resource; such as oil, coal, natural gas, biomass or solar. Natural gas is the most desirable for use in a CCHP system due to availability, reasonable cost, and less environmental impact . During peak load demand hours, it is sometimes necessary to use an auxiliary boiler or electric chiller for heating and cooling. Thus, there is an electrical service connection tied into to the bulk electric grid for purchasing deficit or selling surplus electricity. Recovering and using waste heat for a reliable energy source is what gives CCHP systems the advantage over other types of heating and cooling equipment. (Martens, 1998; Wang, 2002). (Maidment *et al.*, 2002) investigates different CCHP systems used in supermarkets with different cooling and engine technologies. (Mone *et al.*, 2001) investigated the economic feasibility of implementing of CHP systems with existing, commercially available gas turbines and single, double and triple effect absorption chillers.

A typical CCHP system is able to fulfill the energy requirement for its application. There are several components in a CCHP system; such as gas turbine (or reciprocating engine) for the prime mover, a heat recovery steam generator (HRSG) and an auxiliary boiler to produce heating, as well absorption and electrical chiller to supply cooling demand. All these options make energy management a very complex issue. Mathematical modeling techniques are widely used for decision making in such problems. For instance, Rao used LP for analyzing the steam flow balance in a fertilizer process (Rao *et al.*, 1983). Furthermore, in CCHP system, Kong developed basic linear programming modeling for determining the optimum purchased energy consumption (Kong *et al.*, 2005). The assumptions for the demand of electricity, heating, and cooling in a time variable manner, make the problem even more complex. Cardona presented a simplified exergoeconomic methodology based on aggregate data to a trigeneration plant serving a 300bed hospital that is situated in Mediterranean area (Cardona *et al.*, 2006). Thermoeconomic provides a powerful tool for an economic and optimization of energy systems (Díaz *et al.*, 2010). There are several studies carried out in the literature about trigeneration energy systems. (Balli *et*

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al., 2010) reported thermodynamic and thermoeconomic analyses of a trigeneration (TRIGEN) system with a gas–diesel engine. They considered a tri-generation system with an output power about 6.5 MW based on gas-diesel engine.

(Al-Sulaiman *et al.*, 2011) studied the performance assessments of three different tri-generation systems using organic Rankine cycle (ORC) to provide cooling, heating and electricity. In another study (Al-Sulaiman *et al.*, 2011) they performed the exergy analysis of a solar driven tri-generation system. They considered a parabolic through solar collector, organic Rankine cycle, and a single effect absorption chiller. (Huicochea *et al.*, 2011) reported thermodynamic modeling of a tri-generation system consisting of a gas turbine as the prime mover with a double effect absorption chiller. They considered a micro-turbine with 28 kW output power. They also conducted a parametric study to evaluate design parameter effects on system performance. There are also some studies using fuel cells (Tse *et al.*, 2011 and Al-Sulaiman *et al.*, 2011). These studies show the importance of energy and exergy analysis of tri-generation energy systems. As it was discussed earlier, it is important for thermal systems to be economical.

An innovative model for CCHP system is presented in this paper. Both capital costs and purchased energy costs of a variable demand trigeneration plant are selected as the objective function. The operational variables in this design are the absorption chiller and gas turbine sizes, where the sizes of other components are dependent on these two variables. In the proposed method, a set of optimal values for the capital and energy costs are determined in order to produce the lowest total cost.

MATERIALS & METHODS

The CCHP system consists of an absorption chiller (X_1), electric chiller (X_2), auxiliary boiler (X_3), gas turbine generator (X_4), HRSG (X_5) and cooling tower (X_6). The gas turbine is used to meet the electrical demand. The high-temperature exhaust gas of the gas turbine flows through the HRSG to produce high temperature steam. Steam is divided between the absorption chiller and heat exchanger. The function of these components is to help meet the cooling load and to heat exchanger to supply the hot water for domestic use and central heating system separately. There is a heat recovery boiler to help accommodate the heating load if the HRSG heating output does not completely satisfy the demanded. Similarly, if generated electrical power does not meet the demand, the user may purchase electric

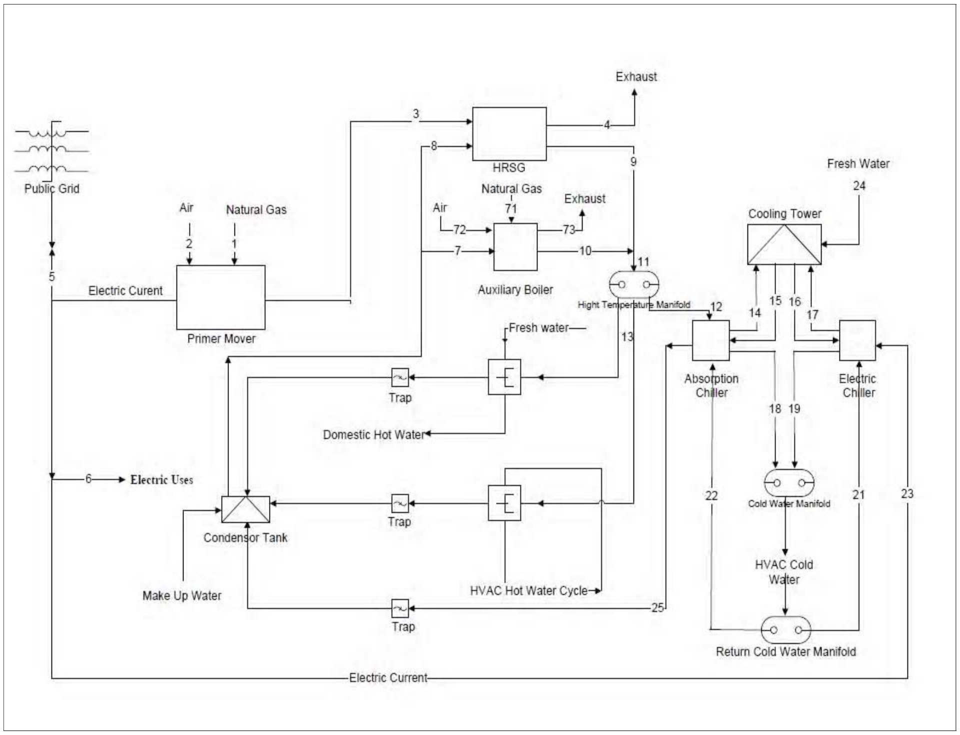

Fig. 1. Flow diagram for CCHP system design

power from electric network. Fig. 1 presents the layout of a gas turbine based CCHP scheme.

The present model is developed on the basis of the above scheme and the following assumptions (Kong *et al.,* 2005):

(i).The exhaust gas, absorption chiller, and heat recovery boiler temperatures are kept relatively constant.

(ii). The efficiencies of equipment are assumed to be constant throughout their operation trajectory.

An innovative model is formulated for minimizing both capital cost of component and total cost of purchased energy needed to meet the cooling, heating and electricity demands under continuous variable demand, all while satisfying the constraints imposed by the physical requirements of the system.

In this analysis, the unit of measurement for the natural gas is m^3/h while the unit for electrical energy is kW, including cooling, heating and electrical loads. The heat value of natural gas is kWh/m^3.

The capacity of all components is dependent on the size of the gas turbine and absorption chiller and it is necessary to find optimum size for the all system components. The objective Function is to consider the capital costs of all components and the total yearly energy consumption costs. Capital cost depends on the size of all components. The gas turbine cost is calculated by means of a cost factor. The energy costs are the total costs of purchased natural gas used in the gas turbine and the auxiliary boiler, and the cost of purchased electrical energy.

CRF is used to determine the annual cost of components, with assumption of 25 years operation, for system (N=25) and %16 interesting factor (i = .16); CRF is given by equation (1):

$$CRF = \frac{i \times (i+1)^N}{(i+1)^N - 1} \quad (1)$$

Thus the objective function is defined by equation (2):

Y= CRF ×(Totalcapitalcost + MaintenanceCost) + EnergyCost

(2)

"Y" represents the total cost of system, and the goal is to minimize this value .The maintenance cost is considered as a portion of purchase cost. In this study, maintenance costs are assumed to be 2% of the capital investment.

As described, the capital cost is the total cost of all components and is defined by equation (3):

Totalcapitalcost = Chiller Abosrptioncost(X1) + Electric Chillercost (X2) + Auxiliary Boilercost (X3) + Gasturbine(X4) + HRSGcost (X5) + Cooling Towercost (X6) (3)

Relations for components cost are presented in Table1.

The Energy Cost is defined by equation (4):

$$EnergyCost = CE_t + CG_t \quad (4)$$

Where CE_t and CG_t represent the total electricity and fuel cost respectively. Total cost of electrical consumption is determined by the electricity cost multiple net value of electric surplus or deficit (ζ) for a year period.

$$CE_t = \sum_{i=1}^{12} CE_i \quad (5)$$

where:

$$CE_i = \begin{cases} \alpha \times \zeta & \zeta \geq 0 \\ \beta \times \zeta & \zeta < 0 \end{cases} \quad (6)$$

$$\zeta = CC_i + DE_i - X_4 \quad (7)$$

$$CC_i = \frac{(DC_i - X_1)}{\eta_{che}} \quad (8)$$

And similarly, the cost of natural gas consumption is an aggregate of consumption of Gas turbine and auxiliary boiler operation over a year.

Table 1. Capital cost of components

Components (X_i) **(X_i is expressed in kW)**	**Capital cost (US$)**
Absorption chiller	Capital cost: $X_1 \times (4253.7 \times X_1^{-0.4662})$
Electric chiller	$X_2 \times (1052.2 \times X_2^{-0.3387})$
Auxiliary boiler	$X_3 \times (1215.8 \times X_3^{-0.4827})$
Gas Turbine	$K_4 \times X_4 \quad (K_4 = 1300 (\$ / kW))$
HRSG	$X_5 \times (1015.8 \times X_5^{-0.4827})$
Cooling tower	$X_6 \times (64.435 \times X_6^{-0.2405})$

$$CG_t = \sum_{i=1}^{12} CG_i \tag{9}$$

where the left hand side is defined as follows:

$$CG_i = \kappa \times CB_i \tag{10}$$

$$CB_i = \frac{NDH_i}{\eta_{boi}} + \frac{X_4}{\eta_{GT}} \tag{11}$$

$$NDH_i = \begin{cases} 0 & TDH_i < X_5 \\ (TDH_i - X_5) & TDH_i > X_5 \end{cases} \tag{12}$$

The component cost factor for the gas turbine (CF_{GT}) is represented in US$/kW and the component size is in kW. Thus the combination of each K with related X is in US$. Similarly, the CE_t and CG_t are in US$. The objective function is in US$ unit.

Thus, Eqs. (1) – (12) provide the tools for a mathematical programming model of the CCHP system. The method used for this energy optimization model is a simple optimization loop wrote in MATLAB software. Using the above optimization algorithm, the optimum size of components for the CCHP system can be determined. In fact, the optimization problem is limited to determination of the size of the absorption chiller (X1) and the gas turbine(X4). The other sizes of the components are as functions of these two parameters.

RESULTS & DISCUSSION

After running the model written in MATLAB, the minimum value of objective function (Y) can be calculated. For this problem, there are three kinds of energy demands for a 12 month period. They are cooling, heating, and electricity needs. These values include 36 data inputs.

In particular, the following yearly demand peaks for a 300-bed hospital situated in a Mediterranean area were calculated (Cardona *et al.*, 2006):

-Cooling demand peak = 1400 kW;
-Thermal demand peak = 1600 kW;
-Electric demand peak = 170 kW;

There are some fixed parameters, such as the efficiency of components as well as electricity and natural gas costs.

The values of 0.67 and 1.75 are COPs of an absorption chiller and electric chiller respectively. The efficiencies of the HRSG and the auxiliary boiler are respectively 0.7 and 0.85. Table2 indicates the cost of natural gas and electricity.

Figure 2 Shows the cost function of system (Y) versus absorption chiller size (X_1) and gas turbine Size (X_4). As it is obvious for the present condition of $X_1 = 1100kW$ and $X_4 = 145kW$, the total cost for the plant is minimum. Therefore, the capacity of the electric chiller (X_2), auxiliary boiler (X_3), and cooling tower (X_6) are easy to find.

$$X_2 = DC_{Max} - X_1 \tag{13}$$

DC_{Max} is the maximum demand of cooling in a year.

$$X_3 = \begin{cases} 0 & TDH_{Max} < X_5 \\ (TDH_{Max} - X_5) & TDH_{Max} > X_5 \end{cases} \tag{14}$$

TDH_{Max} is maximum demand of total heating during a year.

$$X_5 = \frac{X_4}{\eta_{GT}} \times (1 - \eta_{GT}) \times \eta_{HRSG} \tag{15}$$

$$X_6 = (1 + \frac{1}{COP_{cha}}) \times X_1 + (1 + \frac{1}{COP_{che}}) \times X_2 \tag{16}$$

Where COP_{cha} and COP_{che} are the coefficient of performances for the absorption and electrical chillers, respectively.

Thus for $X_1 = 1100kW$, $X_2 = 300kW$, $X_3 = 1684kW$, $X_4 = 145kW$, $X_5 = 237kW$ and $X_6 = 3383kW$ both capital and energy costs of the CCHP system is minimum. For these components sizes, the annual cost of the entire plant is 775,000 dollars.

It is worth mentioning that the optimum value is not the maximum value of demand, but indeed the optimum size of components closely depend on energy demand and energy costs.

Fig. 3 represents the total cost of the CCHP system versus the absorption chiller size for gas turbine sizes 80, 145 and 170 kW. Remember that Electric demand peak for this study is 170 kW.

As it is shown, total cost for $X_4 = 80$ kW is too high, with increasing the gas turbine size (X_4), total cost of the system decrease since $X_4 = 145$ kW that is minimum. After this point, total cost increases with

Table 2. Natural gas and electricity Tariff

Fuel or electricity	Natural gas	Purchased electricity	Sale electricity
Cost (US$/kW)	0.0515	0.104	0.083

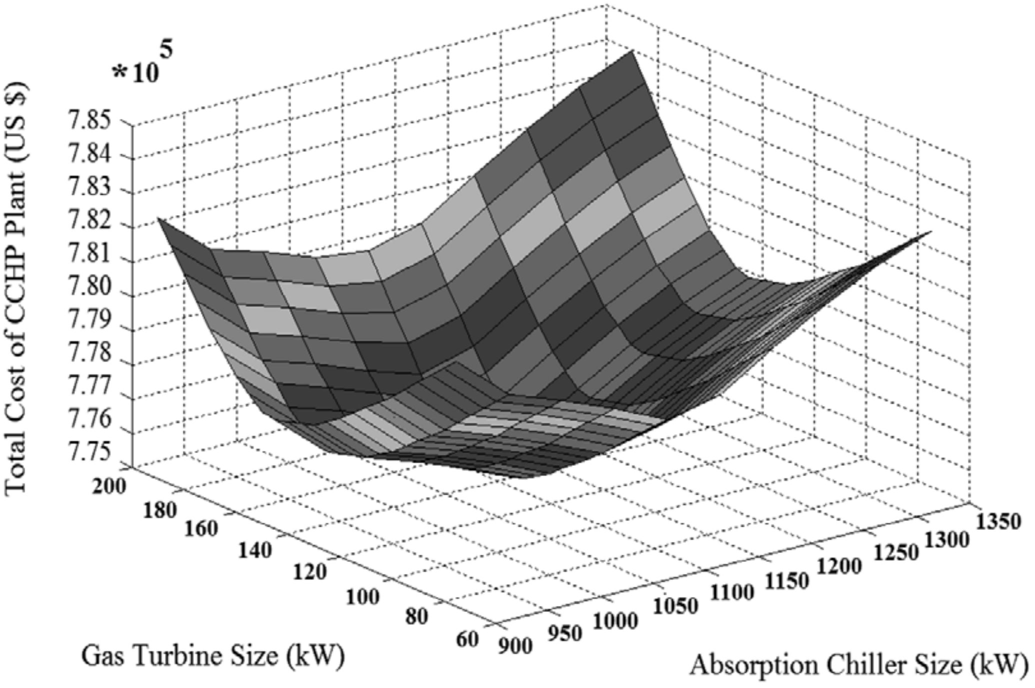

Fig. 2. Cost function of system (Y) vs. absorption chiller size (X_1) and gas turbine size (X_4)

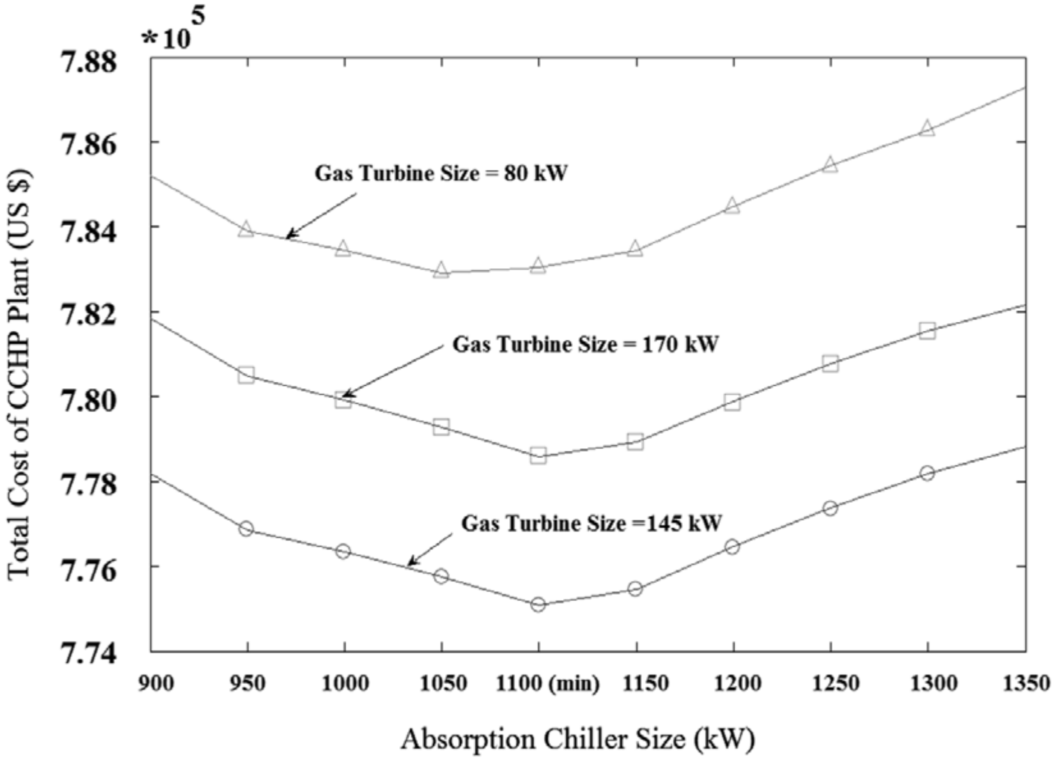

Fig. 3. Cost function (Y) vs. the absorption chiller size (X_1) with gas turbine size (X_4) = 80, 145 and 170 kW

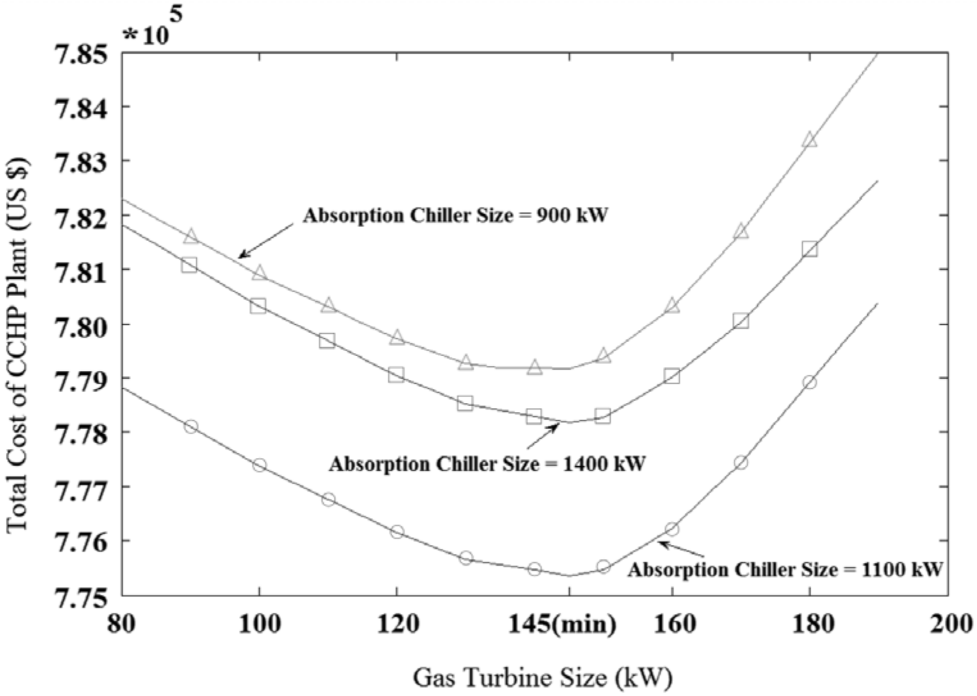

Fig. 4. Cost function (Y) vs. the gas turbine size (X_4) with absorption chiller Size (X_1) = 900, 1100 and 1400 kW

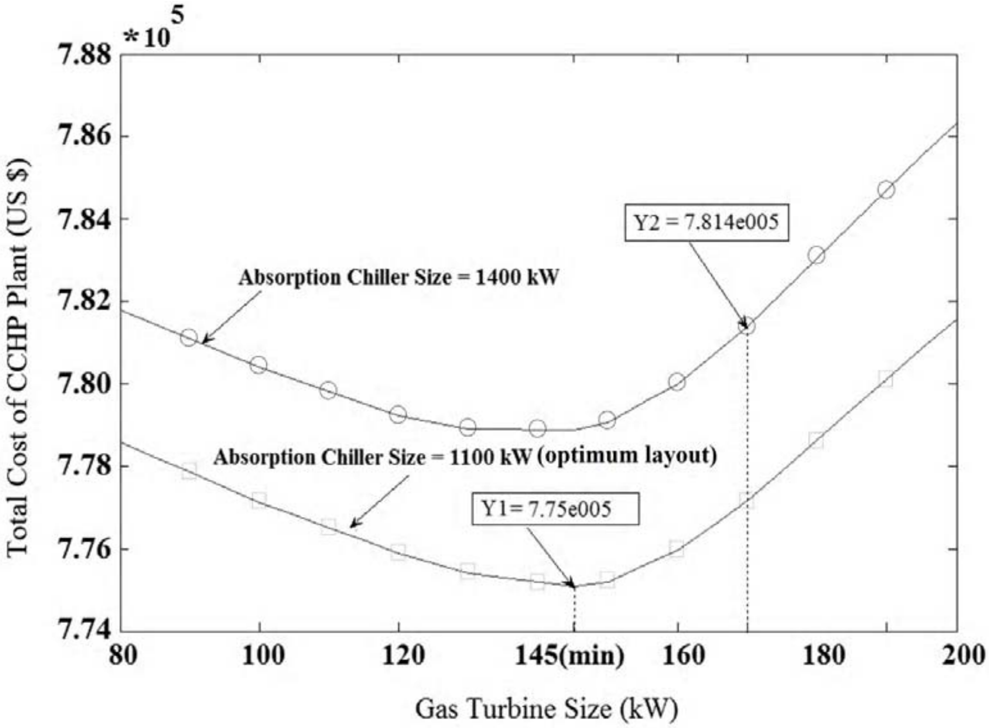

Fig. 5. Total cost of optimum layout (Y1=775,000 dollars) in comparisonwith non-optimum layout (Y2=781,400 dollars)

Table 3. Verification of the optimization method

	Total Cost (USD)
Present Study	$775,000
Cardona *et al*., 2006	$805,000

increasing the value of X_4. For example in X_4= 170 kW (electric demand peak) total cost of plant is more than previous size. Similarly objective function is presented versus gas turbine size for three various sizes of absorption chiller.

It is worth mentioning that the optimum value for the size of absorption chiller is not the peak in the cooling demand. Results show that for providing a refrigeration of 1400kW, the minimum cost value is achieved when refrigeration of 1100kW is provided via absorption chiller and 300kW is provided via electric chiller. For a gas turbine with size of 145kW and an absorption chiller with size of 1100kW, the total cost will be minimum. Selecting the optimum size of the gas turbine and absorption chiller with respect to the demanded electric and refrigeration power would save over $6,300 dollars per year and $150,000 dollars for a period of 25 years. Figure 5 shows optimum layout (Y1) and non-optimum layout (Y2) in one diagram.

For evaluating the accuracy of the proposed method, a comparison has been made between the present study and the results of the Cardona *et al.*, 2006 (Table 3). For both models, the values of the decision variables are X1=1100kW and X4=145kW.

CONCLUSIONS

A new modeling approach is presented to optimize the CCHP system, it has been shown that for present case study with $X_1=1100$ kW, $X_2=300$ kW, $X_3=1648$ kW, $X_4=145$ kW, $X_5=237$ kW and $X_6=3383$ kW, both capital and energy cost of CCHP system are minimized.

Optimization of CCHP systems with variable demand is a complex task, because of the role of many components involved. It was found that the cost parameters especially cost of fuel and purchased electricity, are highly important for finding the optimum operation condition of CCHP plant. On the other hand, the optimum size of the CCHP system depends on the energy demands and energy consumption costs, as well as the capital cost of plant components.

Regarding to the mentioned issues, for a gas turbine with the size of 145kW and an absorption chiller with the capacity of 1100kW, the total cost would be minimum. Selection of the optimum size of gas turbine and absorption chiller, with respect to the demanded electric and refrigeration power, would save over than $6,300 dollars per year and $150,000 dollars for a period of 25 years.

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