DESIGN SUSTAINABLE BUILDING WITH OPTIMIZED COMBINED HEATING, COOLING, AND POWER (CHCP) SYSTEM

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ABSTRACT

In this study, the design and optimization of combined cooling, heating, and power system (CHCP) in a sustainable building complex is dealt with. In these systems, electricity, cooling, and heating are generating using just one primary energy source. The case study in this article is a residential complex in which the monthly energy, cooling, and heating demand is specified. The selection of size of components based on the maximum demand will lead to an increase in the capital cost in a unit. For this purpose, a system was designed in which the prime mover, heat recovery boiler, and absorption chiller is lower than the needed maximum. The difference in months with peak consumption is supplied with the help of absorption chiller and auxiliary boiler (and the national electricity network).

In this study, the optimum capacities of each of the equipment are determined based on thermoeconomic method, in a way that the annual capital cost and energy consumption will be the lowest. The design was done for micro turbine prime mover and reciprocating engine separately, and finally the optimum designs were investigated using exergy analysis, and were compared with a traditional energy supply system.

Keywords: Trigeneration Systems, CHCP, Energy Optimization, Micro Turbine, Thermoeconomic, Sustainable Buildings, Energy Saving.

1. INTRODUCTION

Energy efficiency is the first step toward achieving sustainability in buildings and organizations. Energy efficiency helps control rising energy costs, reduce environmental footprints, and increase the value and competitiveness of buildings. The main objectives of sustainable design are to reduce, or completely avoid, depletion of critical resources like energy, water, and raw materials.

With the cost of energy increasing in recent years, there has been an increase in the interest in energy-saving methods in buildings. One of such methods is using cogeneration systems. Cogeneration or combined heat and power (CHP) is the use of a heat engine or power station to generate electricity and useful heat at the same time with the same fuel. Trigeneration or combined heating, cooling and power (CHCP) refers to the simultaneous generation of electricity and useful heating and cooling from the combustion of a fuel or a solar heat collector. Also Cogeneration is a thermodynamically efficient use of fuel.

Different methods are common in cogeneration in sustainable buildings: one of these methods is the use of combined heating, cooling, and power systems (CHCP). In this method, steam is produced using the output heat from the prime mover. The steam which is produced can be used for heating purpose or be used in an absorption cycle for cooling. When generation of electricity, heat and cooling is done simultaneously in one system, it is called Trigeneration. These systems are used for generation of required energies, including a prime mover for supplying electrical energy in which the use of combustion motor and/or a gas turbine as the primary motor is common. It also includes a heat recovery steam generator (HRSG) for recovery the output energy lost from the primary motor, and the absorption chiller for heat and cold production in the system under investigation. Trigeneration systems cause a return of investment by saving energy. [1-2]

Employing trigeneration systems have wide range of uses in residential complexes, business complexes, hospitals, and other places which have continuous use of energy. In such places, because of the difference in electricity, cold and heat demand in different seasons of the year, the production capacity of each of the equipment of the system can vary. Therefore, the most important parameter in the design and improvement of these systems is the selection of the capacity of each of the equipment.

Usually the capacity of HRSG is determined by determination of the prime mover capacity. The selection of the capacity of the prime mover and absorption chiller based on the maximum demand during the year is not usually economical because of the high capital cost of this equipment, and it leads to an increase in the capital cost in the system [3]. One way is the selection of capacity of this equipment less than maximum demand, and the difference of maximum cold, heat and electricity demand can be provided by compressive refrigeration cycle, auxiliary gas boiler and the national electricity network, respectively. With regards to these, the selection of maximum capacity of equipment can be done by taking into account the varying needs for cooling, heat and electricity during the year.

The optimization of energy consumption in cogeneration systems was done in different domestic and hospital applications [4].

Different methods have been proposed for the determination of optimum capacity of components [5, 6]. E. Cardona and A. Piacentino presented a methodology for determination of prime mover capacity and absorption chiller in Trigeneration system in 2003 [7]. Using Demand Cumulative Curves they determined the suitable capacity for the above-mentioned equipments. In addition to energy saving, this causes a decrease in pollution of the environment.

2. OPTIMIZATION OF HEATING SYSTEMS

One of the common methods for optimization of heating systems is the thermoeconomic method. This method can be used for analysis and improvement of energy systems. The fundamental equation in the thermoeconomic method is as follows:

There are three methods for heating systems according to thermoeconomic method:

1. Minimizing the value of Total Cost, C0; in this method first a thermodynamic analysis then an exergy analysis has to be done on the system, and after determination of C0 its value becomes minimum as the design parameter in the objective function.

2. If the amount of exergy energy (E0) is a constant value during a specific period, C0 can be minimized by minimizing the right hand side of the above equation which is in fact equal to the sum of energy consumption costs and system investment. In this method, there is no need for performing exergy calculations for optimizing the equipment of heating systems; therefore the optimization is done with more ease and preciseness.

3. In some applications, like optimization of recirculation steam boiler, the sum of capital costs and exergy loss are used as objective function [8].

In the present study, a method will be presented based on thermoeconomic analysis, which is in line with obviating the above-mentioned limitations. In this study, the optimization of trigeneration system was done considering the variable cooling, heating and electricity energy demand during the year. This design has been calculated for a residential complex for which monthly consumed energy demand was determined. The method proposed in this article is according to the second method. Minimizing these costs in fact means minimizing costs of generation of heating, cooling and electricity in the system, and as mentioned above, there is no need for exergy calculations for determination of optimum capacity of equipment here. Moreover, in calculation of sum of annual costs, there is no need for averaging; therefore the related error is obviated by averaging.

Also, in this study, optimization for determining the capacity of equipment was done in two modes: continuous and discrete, and for two micro turbine prime mover and reciprocating gas engine, and moreover, the optimized designs are compared with a common energy supply design. Finally, exergy calculations were done for designs, and parameters like exergy output and exergy unit cost of products are calculated.

3. ENERGY REQUIREMENTS AND DESCRIPTION OF TRIGENERATION SYSTEMS

As mentioned above, the cogeneration system intended here is designed for supplying the energy of a residential complex. The energy demands of the case study are as follows [7].

- Maximum electrical energy demand: 32.96 Kilowatt
- Maximum cooling energy demand: 902 Kilowatt
- Maximum heating energy demand: 940 Kilowatt

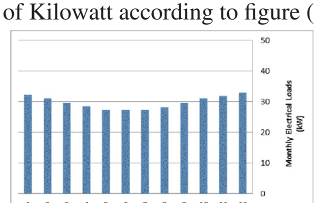
The trigeneration system is consisted of a prime mover, absorption and compressive chillers, and recirculating and auxiliary boilers for supplying the energy demands.

The prime mover in design (1) is a micro turbine and in design (2) is a reciprocating engine, and the recirculating boiler produces saturated steam for heating uses and the steam required in the absorption chiller, and as can also be seen in the schematic of system (Figure 4), the auxiliary boiler is added to the recalculating boiler in times of peak consumption. Also, the absorption chiller performs the required cooling and the compressive chiller supplies cooling demands in times of peak load.

It has to be mentioned that the gas required for prime mover and auxiliary boiler is purchased from natural gas network, and also the electricity for supplying the electricity demand and electricity needed by compressive chiller is provided from the national electricity grid.

4. DEVELOPMENT OF MODEL

As mentioned above, the cogeneration system intended here is designed for supplying the energy of a residential complex. The required energies in this building are electricity, cooling, and heating which have been calculated monthly and in terms of Kilowatt according to figure (1) to (3) [10].



As can be seen, the maximum consumption energy demand is as follows:

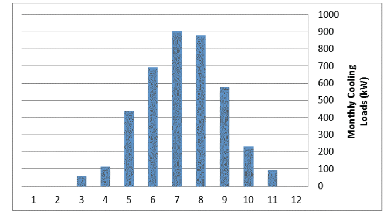


Figure 2 : Monthly Cooling Loads

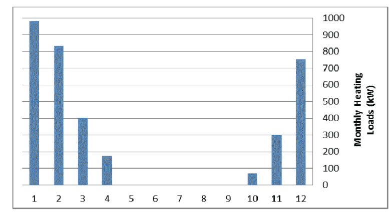
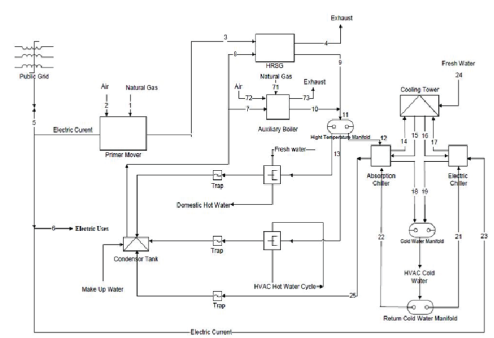


Figure 2 : Monthly Cooling Loads

Maximum electrical energy demand: 33 Kilowatt,
Maximum cooling energy demand: 902 Kilowatt,
Maximum heating energy demand: 940 Kilowatt

The trigeneration system is consisted of a prime mover, absorption and compressive chillers, and recirculating and auxiliary boilers for supplying the energy demands. Figure (4) indicated the design of trigeneration system.



The prime mover in design (1) is a micro turbine and in design (2) is a reciprocating engine, and the recirculating boiler produces saturated steam for heating uses and the steam required in the absorption chiller, and as can also be seen in the figure, the auxiliary boiler is added to the recirculating boiler in times of peak consumption. Also, the absorption chiller performs the required cooling and the compressive chiller supplies cooling demands in times of peak combustion.

It has to be mentioned that the gas required for prime mover and auxiliary boiler is purchased from natural gas network, and also the electricity for supplying the electricity demand and electricity needed by compressive chiller is provided from the national electricity network.
The sum of capital cost and energy consumption is assumed as target function, which is the statement at the right side of equation (1). Therefore, the target function will be equal to:

$$Y = \text{Energy Cost} + \text{Capital Cost} \qquad (1)$$

In other words:

$$Y(\$) = \text{Annual Capital Cost}(\$) + \text{Annual Energy Cost}(\$) \qquad (2)$$

Where the sum of costs is calculated for one year and is in Dollars. The right side of the equation above, which are the annual energy costs and capital costs are a function from capacity of system components.
The capacity of each of the components of the system is determined in Kilowatts (kW), and is as follows:

X1: absorption chiller capacity
X2: compressive chiller capacity
X3: auxiliary boiler capacity
X4: prime mover capacity
X5: heat Recovery boiler capacity
X6: cooling tower capacity

Therefore, the two statements at right side of equation (2) will be as follows:

$$\text{Annual Capital Cost } (\$) = F(X1,\dots, X6) \qquad (3)$$

As a result, the target function will be like the following:

$$\text{Annual Energy Cost } (\$) = F(X1,\dots, X6) \qquad (4)$$

Where X1 to X6 are capacity of component in trigeneration system in Kilowatts (kW), As a result, the objective function will be like the following:

$$\text{Min } Y = \text{Annual Energy Cost } (X1,\dots,X6) + \text{Annual Capital Cost } (X1,\dots,X6) \qquad (5)$$

Considering the cogeneration system presented here and the thermodynamic conditions of the system, the capacity of components of the system can be written according to the capacity of two major components of the system, prime mover (X4) and absorption chiller (X1).
In other words the capacity of components in CHCP system (X2, X3, X5 and X6) should be written as function of X1 and X4.

Therefore, the target function of the system which includes the annual capital cost and energy consumption in the complex in one year is written as a function from capacity of components of the system where all the statements are in Dollars. So, the objective function of the system includes annual capital costs and energy consumption, and the capacity of absorption chiller (X1) and prime mover (X4) are the design parameters of the objective function. After performing optimization, its optimum value and as a result the optimum values for all components of the system are obtained.

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5. RESULTS

Deterministic optimization is chose as the optimization approach for finding the optimum values of X1 and X4. Therefore the minimum of the plotted surface is the global optimum of objective function. The results of the objective function is calculated and shown in Figure 5 and 6 (programming in MATLAB). In the second stage of optimization, with regards to the equipments available in the market, the optimum size of components was determined for building by modeling in EES software based on thermoeconomic method. This modeling and comparing energy consumption also economical index will be demonstrated.

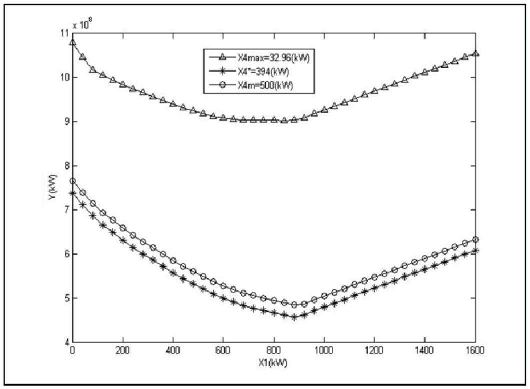

Figure 5: Values of X_4 via X_1 in Maximum Demand, Minimum demand & Optimum Value

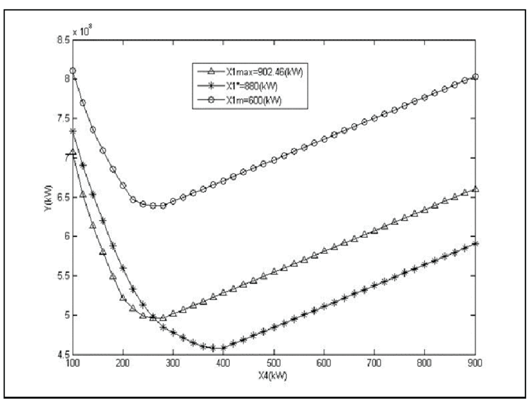

Figure 6. Values of X_4 via X_1 in Maximum Demand, Minimum demand & Optimum Value

Also the optimized CHCP (Optimized by MATLAB Programming) are present in Table 2 and 3, these results show optimization for two layouts of CHCP with two kinds of prime movers.

Table 1: Optimal size of CHCP system with Gas Turbine prime mover (Layout 2)

Component	Optimal Size (kW)
Absorption Chiller (X_1)	579
Auxiliary Chiller (X_2)	323
Auxiliary Boiler (X_3)	161
Gas Turbine (X_4)	230
HRSG (X_5)	828
Cooling Tower (X_6)	1810

Table 2: Optimal size of CHCP system with Gas Engine prime mover (Layout 3

Component	Optimal Size (kW)
Absorption Chiller (X_1)	880
Auxiliary Chiller (X_2)	22
Auxiliary Boiler (X_3)	330
Gas Engine (X_4)	394
HRSG (X_5)	540
Cooling Tower (X_6)	2165

Also to provide the energy demand in ordinary traditional energy systems (Separated Heating and Power Systems, SHP), we should have such components (Table 3).

Table 3: Normal size of ordinary SHP system (Layout 1)

Component	Optimal Size (kW)
Absorption Chiller (X_1)	914
Gas Boiler (X_3)	1860
Cooling Tower (X_6)	2038

So Total Energy efficiency of all three layouts and Rate of Return period of capital cost (ROR) in two first layouts are calculated and shown in below (figure 7).

Overall efficiency in layout 1 (without combined system) is about 44%, it is a domestic power and energy (cooling and heating) system as common energy system. But as calculated above, total efficiency of CHCP system with Gas Turbine prime mover is about 80% for total system. Also 84% was calculated for CHCP system with Gas Engine motor as prime mover.

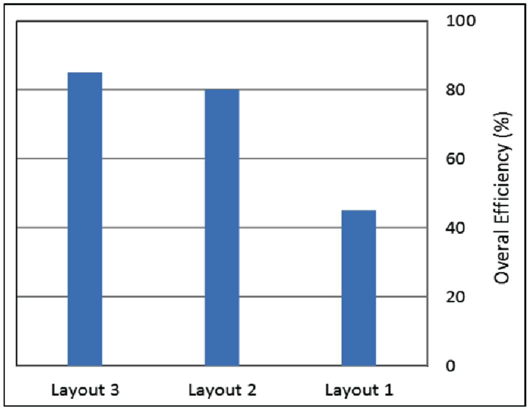

Figure 7: Overal Efficiency of three Layouts (%)

It can be show that at least 30 percent saving will be occurred by using optimized CHCP system for new sustainable buildings. Figure 7 shows thermal efficiency of these 3 kinds of systems (CHCP system with Gas Turbine Prime mover, CHCP system with Gas Engine Prime mover & traditional system (Seprated Heat & Power, SHP, System)).

Also As can be seen Payback Period of of CHCP systems are demonstrated in Figure 8. Payback period of these two sample CHCP systems are about 5 & 8 years because of energy saving in period of operating system. Therefore CHCP systems not only cause to energy saving and reducing energy cost in buildings but also make our worlds cleaner and lees pollutions.

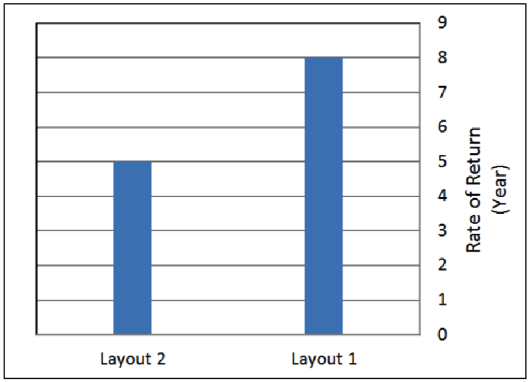

Figure 8. Payback Period in CHCP systems (years)

6. CONCLUSION

Energy efficiency over the entire life cycle of a building is the most important goal of sustainable architecture. Architects use many different passive and active techniques to reduce the energy needs of buildings and increase their ability to capture or generate their own energy. One of the effective methods to reduce energy consumption is applying CHCP systems in buildings.

CHCP systems not only reduce the consumption of fuel and the cost of energy in system but also reduce the capital cost and cost of products.

CHCP systems also reduce air pollutions, in this study optimized sustainable system applied in case study saved more than 30 percent energy of fossil fuel. It leads to more clean air and also cleaner environment.

In this paper two different kind of trigeneration system were used as sustainable energy system to provide power (electricity), heating and cooling energy as energy demand of building. Study showed that optimized CHCP systems are extremely more efficient compare with separated ordinary traditional energy systems. CHCP systems are at least 35% more efficient and it means less fuel and less environment pollutions.

Gas engines are so proper for CHCP systems, with apply gas engine in CHCP the exergy and energy unit cost of products are at least one third of the value in SHP systems that are conventional in most residential plant.

Also calculations also showed that return rate of investment in these systems are very short and less than 5 years (for gas engine prime mover system). Therefore this study showed that applying trigeneration systems in sustainable buildings are certainly economic.

7. ACKNOWLEDGEMENTS

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