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Full Length Research Paper

Economical analysis of trigeneration system

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Trigeneration systems should be designed to supply all energy demands of a new facility and increase the profit of an existing facility. In this paper, a model to determine optimum capacity of trigeneration systems that maximizes the present value of the net profit has been developed to embed trigeneration systems to existing systems. Proposed economical model has been employed on a university campus. Considering the electricity, heat and chilling demand of the campus and the characteristics of existing system, optimum trigeneration capacity and operation strategy has been defined.

Key words: Economical model, operation strategy, trigeneration system.

INTRODUCTION

Importance of the trigeneration systems is increasing day by day due to the growing energy demand and increased environmental awareness. With the concept introduced by trigeneration systems it is possible to obtain electricity, heat and chilling step by step firing the same fuel. Thus, not only utilization of the fuel is increased but also emissions are decreased substantially compared to conventional systems in which these three forms of energy are generated individually.

Studies conducted on trigeneration systems are generally deals with new system design or employing a trigeneration system only as a replacement to the existing conventional system (Temir, 2004; Calva, 2005; Ziher, 2006; Cardona, 2003; Santoya, 2003; Chicco, 2008; Mancarella, 2008; Arteconi, 2009; Silvera et al., 2002). In some of these studies, trigeneration system has been designed which are capable to deliver the three forms of energy demand; electricity, heat and chilling (Temir, 2004; Cardona, 2003; Ziher, 2006; Arteconi, 2009). However, dealing with more than one energy form mandates to various systems in terms of design and operation. One of the main reasons of this mandatory situation is the fluctuation of the demands of three energy forms throughout a year (Carvalho, 2010). Thus, base energy form out of these three forms plays the key role in determining capacity of the trigeneration system and operation strategy (Lai, 2009; Rong, 2005).

Amount of the other two forms of energy that can be delivered by the trigeneration system depends on this base energy form and the designed system features. Various approaches can be implemented for this issue:

(i) Trigeneration system can be designed and operated to supply all the electricity demand (Emho, 2003). Besides, total electricity demand corresponding to chilling demand that is supplied by the trigeneration system should also be subtracted from the total electricity demand. In case heat demand is higher than the capacity delivered by the trigeneration system, then this excess demand is supplied by a conventional boiler. Capacity of this boiler should be determined according to the amount of the excess heat demand. If heat generation is higher than the demand, then heat will be rejected to environment and thus, fuel utilization will diminish.
(ii) Trigeneration system can be designed and operated to supply all the heat demand. In this concept, trigeneration system is connected to the main power grid and excess electricity generated by the system is sold to main grid and in case demand is higher than the generation, then electricity is supplied from the grid. Heat demand can vary seasonally or periodically. This fluctuation affects both electricity and chilling energy generation of the system.
(iii) Three generation systems can be designed and operated to supply sometimes electricity and sometimes heat. For this type of operation, energy demands should not fluctuate. Besides, system should be integrated to

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main power grid and a supplementary boiler should be installed.

Most feasible trigeneration system can be implemented if a chilling and heat system exist and operational to support the trigeneration system. Utilizing the existing systems would affect both capacity and operation strategy of the trigeneration system. Besides, cost avoidance for additional investment due to existing system results in a considerable economical advantage. However, not only determining the right capacity is adequate but also a structured and sound operation strategy is also needed for an economical point of view (Lai, 2010). Utilizing the rejected heat from the trigeneration system for heat or chilling purposes is especially important for the economical benefits of the system.

In this paper, an operation model has been constructed that takes into account not only the peak values of the demand energy form as in the classical approaches, but also the operational conditions depending on the energy demand (electricity, chilling and heat) on hourly basis. For this purpose, an economical model has been constructed to determine the optimum capacity and operation strategy for a trigeneration that will be embedded to an existing system. Production costs of the existing system and the costs of investment, operation and maintenance of the trigeneration system has been considered in the model. Present value of the net profit has been used for economical comparison and trigeneration capacity and operational conditions that maximize this value had been determined. Partial load characteristics of the system depending on the supply/demand ratio throughout the year had also been considered. Proposed economical model had been employed on a university campus. Considering the electricity, heat and chilling demand of the campus and the characteristics of existing system, optimum trigeneration capacity and operation strategy has been defined.

ECONOMICAL MODEL

Representative drawing of the trigeneration and existing system model that supplies all the energy demands of a facility is shown in Figure 1. In the existing system, electricity demand is supplied from the public network, heat demand is supplied with a boiler and chilling demand is supplied with a mechanical chiller. Also the energy flows employed in the economical model have been shown in this figure.

In the first stage energy demands, electricity and heat prices for a typical year are written in the model. Afterwards, trigeneration system is embedded to the model considering maximum and minimum electricity demand. Thermal efficiency, electricity/heat ratio and COP values which are dependent on the kind and load of evaluated three generation system, are inserted to the model and consequently, model determines the hourly electricity and heat capacity. Model chilling capacity is determined between minimum and maximum chilling loads in order to define allocation of thermal capacity on chilling and heat purposes. Model changes chilling capacity in order to minimize the economical value of energy forms that cannot be supplied by trigeneration system (supplementary energy). Thus, energy rejected by the trigeneration system is allocated to the heat and chilling duties. Model calculates the costs depending on these energy capacities and trigeneration system capacity that maximizes the net profit is determined accordingly.

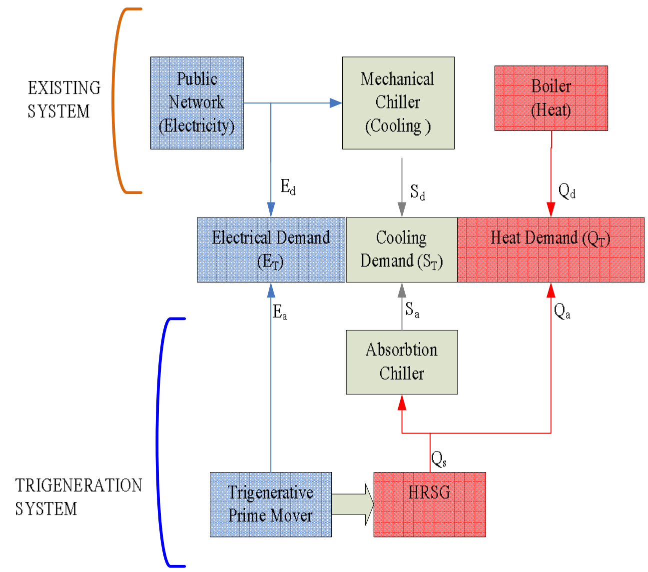

Figure 1. Model concept of energy supply for trigeneration and existing system.

Firstly, model determines the operational costs for current situation depending on energy demands. An operational cost in terms of cost per hour (C_1) is given in Equation 1.

$$C_1 = E_T f_e + Q_T f_y \frac{1}{\eta_k} + S_T f_e \frac{1}{COP_{ac}} \quad [\$/h] \qquad (1)$$

In this equation, E_T stands for electricity demand, Q_T for heat demand, S_T for chilling demand, f_e for electricity demand, f_y for fuel price, η_k for boiler efficiency, COP_{ac} for coefficient of performance of the chilling system.

Operational costs of the facility arise from three different cost types when a trigeneration system is added to the existing facility. These are; operational and maintenance costs of the trigeneration system (C_{TR}), supplementary electricity cost supplied from existing system (C_{Ed}) and supplementary fuel cost (C_{Od}). Total operational and maintenance costs (C_2) of a trigeneration embedded system are given in Equation 2 in terms of cost per hour.

$$C_2 = C_{Qd} + C_{Ed} + C_{TR} \quad [\$/h] \qquad (2)$$

Supplementary fuel cost occurs when heat demand (Q_T) is higher than the heat capacity (Q_a) delivered the trigeneration system. In this case, this differential heat is supplied from the existing boiler facility. Supplementary fuel cost (C_{Od}) depending on lower heat value of the fuel (LHV), boiler efficiency and fuel price is given in Equation 3.

$$C_{Qd} = \frac{(Q_T - Q_a) f_y}{LHV \, \eta_k} \quad [\$/h] \qquad (3)$$

Supplementary electricity cost occurs when electricity demand (E_T)

is higher than the electricity capacity (E_a) delivered the trigeneration system. Also, differential energy between the capacity delivered for chilling (S_a) and the demand for chilling (S_T) is supplied from existing grid. Cost of supplementary electricity (C_{Ed}) is stated in Equation 4, depending on performance of coefficient of the chilling system and electricity price.

$$C_{Ed} = \left[(E_T - E_a) + \left(\frac{S_T - S_a}{COP_{ac}} \right) \right] f_e \quad [\$/h] \qquad (4)$$

Operational and maintenance costs (C_{TR}) of the trigeneration system would vary depending on the technical characteristics of the system. Supply of electricity is the main approach of embedding trigeneration system to the existing system. However, the amount of electricity that will be supplied by the trigeneration system is determined by maximization of net profit. This approach has been chosen due to the fact that existing system has a boiler and connected to main electricity grid. Thus, electricity capacity (E_a) of the trigeneration system becomes the leading parameter for cost determination. Besides, thermal efficiency (η) of trigeneration system as well as with the operational and maintenance costs (C_{om}) has been considered for also partial loads.

$$C_{TR} = E_a \frac{1}{\eta} f_y + E_a C_{om} \quad [\$/h] \qquad (5)$$

Amount of heat (Q_s) that can be generated by trigeneration system can be calculated with the help of electricity/heat ratio (θ).

$$\theta = \frac{E_a}{Q_s} \qquad (6)$$

Thermal capacity of trigeneration system is the sum of the heat capacity (Q_a) and chilling capacity (S_a) of the absorption system.

$$Q_s = Q_a + S_a \frac{1}{COP_{ab}} \qquad (7)$$

Here, important point is the allocation of thermal energy overheat and chilling. A minimum operational hour of the chilling system is the limiting condition to determine this allocation. If the system is below the minimum limit than there is not any chilling supply, and upper limit is determined as the chilling demand at the specified time.

$$\alpha S_a \leq S_a \leq S_T \qquad (8)$$

Decision parameter is the total cost of additional fuel and additional electricity (C_D), since the difference between demand and supply of heat and chilling is satisfied from the existing system. Chilling supply is determined to minimize this total cost and afterwards associated heat supply is determined accordingly.

$$C_D = C_{Ed} + C_{Qd} \quad [\$/h] \qquad (9)$$

After determining the energy supplies of the trigeneration system, costs of the existing system and trigeneration system are calculated annually regarding hourly costs and difference between these two figures gives out the annual gain (Equation 10). If this annual gain is calculated over the economical life of the system then net present value of the lifetime profit (C_{pw}) can be found (Equation 11). In this

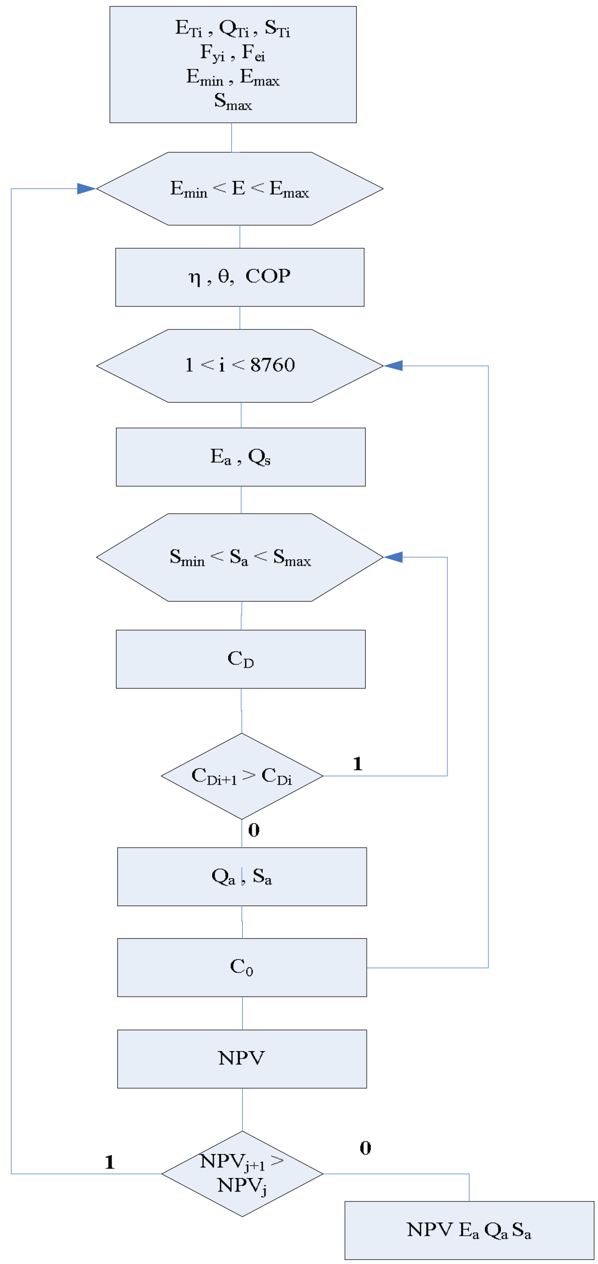

Figure 2. Flow chart of the economical model.

equation t stands for year, n stands for economical life of trigeneration system, e stands for escalation and r stands for discount rate.

$$C_o = \sum_{i=1}^{8760} \left[C_{1(i)} - C_{2(i)} \right] \quad [\$/\text{Year}] \qquad (10)$$

$$C_{pw} = \sum_{t=1}^{n} C_{0(t)} (1+e)^t (1+r)^{-t} \quad [\$] \qquad (11)$$

Investment cost of the trigeneration system (C_{yat}) has been stated in Equation 12 as unit costs of the power system (K_T) and absorption

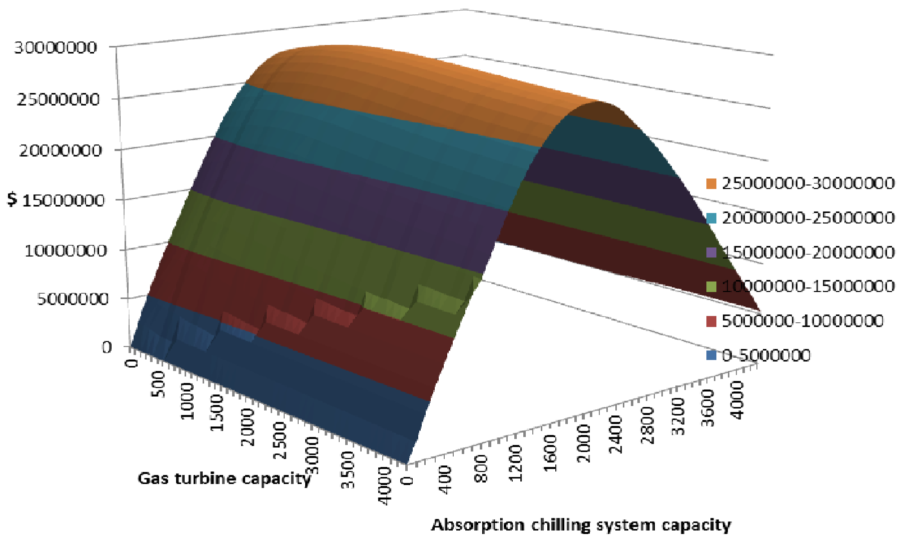

Figure 3. Results of the optimization.

Table 1. Assumed values that had been employed for the model.

Thermal efficiency of the existing boilers	90%
COP value of the existing chilling system	3,76
COP of absorption chilling system	1
Lower operational capacity limit of absorption chilling system	25%
Electrical load of absorption chilling system	0,08 kW_e/kW_s
Power generator electrical efficiency on full load operation	29%
Lower operational capacity limit of power generator	50%
Power/heat ratio of power generator	0,66
Operational and Maintenance Costs	0,010 $/kW$_e$h
Investment cost of gas turbine	1380 $/kW$_e$
Investment cost of absorption chilling system	123,33 $/kW$_s$
Economical life of trigeneration system	16 years
Discount rate (per year)	7,5%
Escalation (per year)	7%

system (K_{ab}) depending on supplied electricity and chilling.

$$C_{yat}=E_aK_T+S_aK_{ab} \qquad [\$] \qquad (12)$$

Thus, present value of the net profit obtained by installing a trigeneration system is found.

$$NPW=C_{pw}-C_{yat} \qquad [\$] \qquad (13)$$

Flow chart of the developed model is shown in Figure 2 (Sancar, 2009).

Case study

Model has been implemented to a university campus. Electricity of the campus is supplied from the existing electricity grid. Campus has 2 units of 4500 kW and 1 unit of 2000 kW mechanical chiller and 3 units of 6500 kW_t and 1 unit of 3000 kW_t boiler. Heat and chilling consumptions of the campus had been measured on hourly basis, by means of calorimeters installed on corresponding pipelines. Besides, electricity consumption also had been measured and given in Figure 3.

Three-way tariff of Turkish Distribution Company TEDAS had been considered as electrical grid tariff (0,236$/kW$_e$h for peak period at 17.00–22.00, 0,100$/kW$_e$h for night period at 22.00–06.00, 0,157$/kW$_e$h for daytime period at 06.00–17.00). Natural gas had been selected for the model as fuel of existing system and trigeneration system. Actual price of natural gas is the price of distribution company IGDAS, which is 0, 038 $/kW$_t$h.

Gas turbine with absorption system had been selected as trigeneration plant. Thermal efficiency variation of gas turbine for partial loads had been considered in the model. Assumptions of the model are shown in Table 1. Gas turbine and absorption system capacities have been started from 0% and present value of the net profit has been calculated when employing the model. Optimization had been stopped for the cases where present value of the net

Table 2. Energy generation and operational hours of the gas turbine trigeneration system to be installed.

Operating hours of the trigeneration system	7440	Hours/year
Electricity production of the gas turbine	13123802	kW_eh/year
Heat supplied by the gas turbine	12157746	kW_th/year
Chilling supplied by the absorption chilling system	2414937	kW_sh/year
Heat supplied by the existing boiler	4747653	kW_th/year
Chilling supplied by the existing chilling system	1304562	kW_sh/year

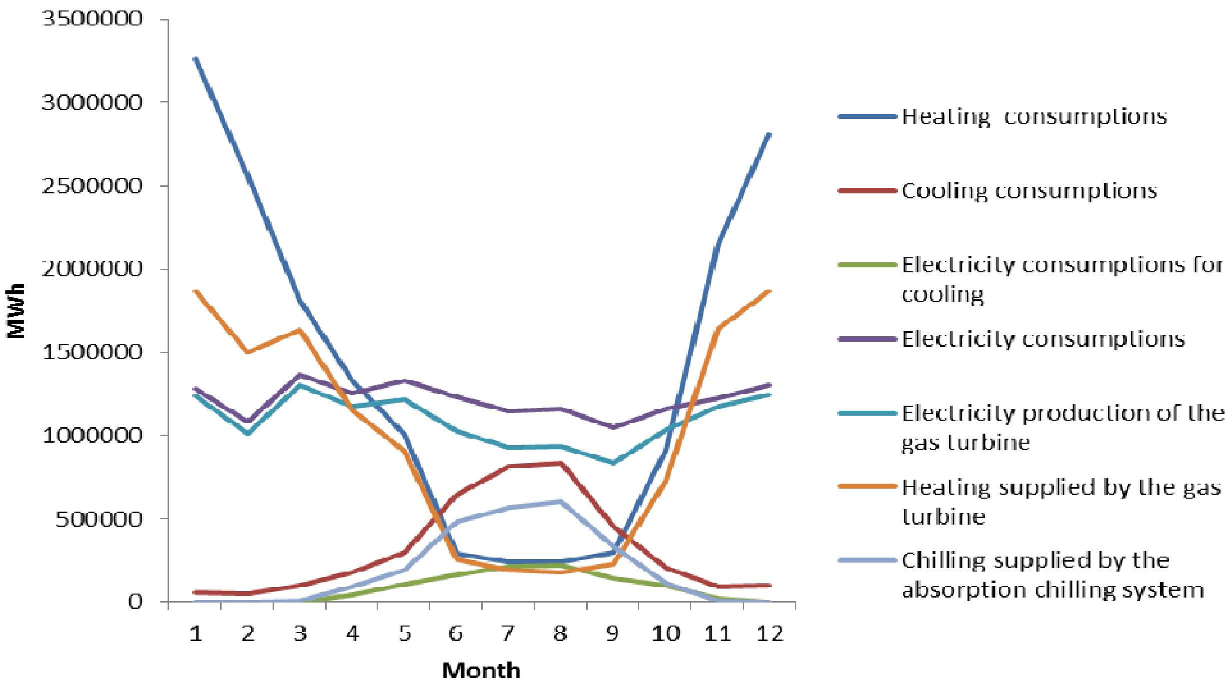

Figure 4. Relationship between energy demands and energy production of trigeneration system.

profit goes below 66.66 \$. According to these statements and assumptions, results obtained from the model are shown in Figure 3.

Variation of net present value of the net profit depending on gas turbine and absorption system capacity has been shown in Figure 3. Considering this variation, maximizing the net profit capacities are 1963, 60 kW_e - 1510, 18 kW_s and amount of corresponding present value of the net profit is 29,478,757.85 \$.

Developed model selects the most possible real system from the database (Gas Turbine World, 2008) considering the optimum results. Alstom GT2 gas turbine which has a capacity of 2130 kW_e, electricity/heat ratio 0.66 and 28% efficiency has been selected as real turbine. For this turbine, chilling capacity would be 1510 kW_s.
Operational status of the trigeneration system and the existing system are shown in Table 2.

Coverage of the trigeneration system energy forms compared to demand energy forms and the variation of this coverage are shown in Figure 4. According to Figure 4, trigeneration system that maximizes the present value of the net profit is not able to cover all of the demands. Existing system is also operated to support the trigeneration system. Present value of the net profit for these operational conditions of the trigeneration system is 29,319520 \$.

RESULTS AND DISCUSSION

Trigeneration systems have a key role for efficient primary energy resources. Trigeneration systems should be designed to supply all energy demands of a new facility and increase the profit of an existing facility. In this paper, a model to determine optimum capacity of trigeneration systems that maximizes the present value of the net profit had been developed to embed trigeneration systems to existing systems. Even though this specific capacity may vary with economical and technical conditions, it should be high enough to supply all energy demands of the system. Especially, distribution between energy forms has an important effect on this capacity and seasonal variation of this distribution also affects the capacity. Capacity of a trigeneration system that would supply all energy demands of the system would be so high that full load duration of a such trigeneration system would be so low and consequently posses high amounts of

Table 3. Annual energy consumptions of university campus and forms of energy supplied by trigeneration system.

	Electricity (kW_eh)	Heat (kW_th)	Chilling (kW_sh)
Demand	15611288	16905400	3837500
Trigeneration supply	13123802	12157746	2414937
Coverage ratio	0.84	0.72	0.63

investment and operational costs. Since trigeneration system will be embedded to an existing system for the developed model, peak demands can be supplied by the existing system. Thus, investment cost would be decreased and annual operation would increase with full load which result in lower operational costs.

Developed model for this study calculates the operational and maintenance costs of the existing system depending on hourly demands, considering the partial loads characteristics of a system that would supply these demands model determines investment, operational and maintenance cost for the operation of trigeneration system with the existing system. These costs are evaluated by the model according to the present value of the net profit and model determines the capacity of the trigeneration system that would maximize this present value. Model creates a capacity which is lower than the system demand. Thus, model should consider the effect of the existing system on the trigeneration system capacity and costs. Annual energy demands and coverage by the trigeneration system for the case study have been shown in Table 3. According to this table, optimum trigeneration system supplies 84% of electricity demand, 71.9% of heat demand and 62.9% of chilling demand. Remain demands are supplied from the existing system. For these operational conditions present value of the net profit is 29,319,520 $. Since cost of the trigeneration system to be installed is 50, 340, 13.33 $, payback period would be 10 months.

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