Proceedings of the Fourth IASTED International Conference
POWER AND ENERGY SYSTEMS (AsiaPES 2008)
April 2-4, 2008 Langkawi, Malaysia
ISBN CD: 978-0-88986-732-1

OPTIMAL DESIGN OF A COGENERATION SYSTEM FOR TYPICAL HOSPITALS IN MALAYSIA

Abu Hanifah Azit and Khalid Mohamed Nor
Universiti Teknologi Malaysia
Malaysia
e-mail abuhanifah@tnb.com.my

ABSTRACT

Hospital is one of the potential facilities that could employ cogeneration system. This high efficiency energy conversion system could offers a lots of benefit especially savings on the energy used. Furthermore, it is very effective compared to centralize bulk generation if it is sited near the load. To reap the maximum benefit, a cogeneration system must be optimally sized.

This paper presents a study of cogeneration system for typical hospital buildings in Malaysia. A mixed integer non-linear optimization technique is used to size the system. A Newton Raphson and Conjugate method have been used in the optimization process. The optimization technique models the cogeneration system together with a thermal storage system that will provide broader spectrum in the optimization exercise.

Hospital facility with maximum demand of 5 MW and 2 MW are simulated. The annual savings will be optimized operationally by varying hourly generation output. Matching the generated electrical and thermal energy to the load will be optimized. Having thermal storage in the model will enhance the matching procedure towards better overall efficiency. Five different capacities of gas turbine generator that are available commercially are used in the simulation to determine the choice of optimal size system. This model and its solution are suitable for cogeneration facility planning study.

KEY WORDS
Cogeneration, Modeling and Optimization

Nomenclature

$I(j)$	Input energy to turbo generator
$E_E(j)$	Electrical energy output
$E_H(j)$	Thermal energy for heating load
$E_{ice}(j)$	Thermal energy from ice storage
$E_{abs}(j)$	Thermal energy from absorption chillers
$E_{\max}(j)$	Maximum capacity of turbo generator
$E_{L1}(j)$	Thermal loss at HRSG system
$E_{L2}(j)$	Thermal loss at absorption chiller system
$E_{L3}(j)$	Thermal loss at ice storage system
$G_E(j)$	Top-up energy from the grid (electrical load)
$G_H(j)$	Top-up energy from the grid (heating load)
$G_C(j)$	Top-up energy from the grid (cooling load)
$L_E(j)$	Electrical load
$L_H(j)$	Heating load
$L_C(j)$	Cooling load
$X_E(j)$	Excess electrical energy
$X_T(j)$	Excess thermal energy
$G_P(j)$	Top-up peak energy
$G_{OP}(j)$	Top-up off-peak energy
D_{tu}	Top-up demand
D_{sby}	Standby demand
W	Water consumption
r_1	Fuel cost
r_2	Peak energy rate
r_3	Off-peak energy rate
r_4	Water rate
r_5	Top-up demand rate
r_6	Standby demand rate
r_7	Selling of electricity rate

1. Introduction

Cogeneration system produces electricity and heat at decentralize location that is where both form of energy are required. They offer optimal efficiency in the transformation of energy with minimum environmental pollution. Hospital that has a significant thermal load is one of the potential facilities to use cogeneration system. However, the system has to have the right sizing especially the size of the generator, in order to obtain the optimal benefits on the total annual cost savings.

Most optimization for sizing exercise uses a mixed-integer nonlinear programming approach [1][2]. Earlier the sizing is done by using a conventional approach that is by examining actual case studies to set up correlations that allow sizing of main components [3]. However, the conventional approach unable to guarantee an optimum solution because its analysis uses limited options. Even though optimization approach is used, the optimum solution obtained is not necessarily the best because the optimal result depends greatly on the accuracy of the load model and the optimization model itself [4].

The previous studies that have been done did not model the cogeneration system in total [1][2][3]. The optimization objective does not attempt to maximize the overall net cost saving. Various cost elements such as topping up energy cost, standby cost, selling of excess electricity energy are not included in the optimization process [1][2][3]. Apart from that, the studies did not include thermal storage to manage the excess heat that enables to improve the overall efficiency of cogeneration system.

The generator size has been treated as a continuous variable that is not true in practice as commercially available cogeneration gas turbine comes in a number of fixed sizes [1]. In addition generators of different sizes have different thermal characteristics therefore they have to be model separately especially on the thermal output efficiency.

In this paper, a more comprehensive model that takes into account the above issues is used. Topping up energy cost is included because cost of energy generated by cogeneration varies while the cost of top up energy is constant (depends on utility tariff). Therefore there is a need to optimize on how much to generate and how much to top up. Standby cost is included in the model because in practice the facility needs to have a continuity of supply when the cogeneration system is not available due to maintenance or force outage. Peak and off peak energy cost is included in the model to reflect the true practice of energy costing in Malaysia. Thermal storage is also included to manage the excess thermal energy. The optimization decisions whether to top up or generate and store the thermal energy will be made based on the cost of energy.

Generally, the optimization is done by optimizing the energy balance between various components in the model and converts them to monetary value to determine the optimum annual cost savings. Thermal storage that is also part of the model will enhance the matching of the generated thermal energy to thermal load hence improving the overall efficiency. The hourly-generated electrical energy is the optimization variables. The thermal and electrical energy balance is the functional constraint and the limit constraints are from the characteristics of the system components. The decision of how much energy to be generated, how much to top up and how much to store will be optimize to result in an optimal annual savings.

A typical hospital facility in Malaysia with a maximum demand of 5 MW and 2 MW will be simulated. Gas turbine cogeneration is used in the model. Five standard size commercially available gas turbines are used in the simulation.

2. Load Modeling

One of the critical data input in cogeneration simulation is the load data. At least it has to be represented as a chronological hourly load. The ideal case is represented by 8760 hours per year. However, the 8760 hours of load could equally represent by a typical representative loads.

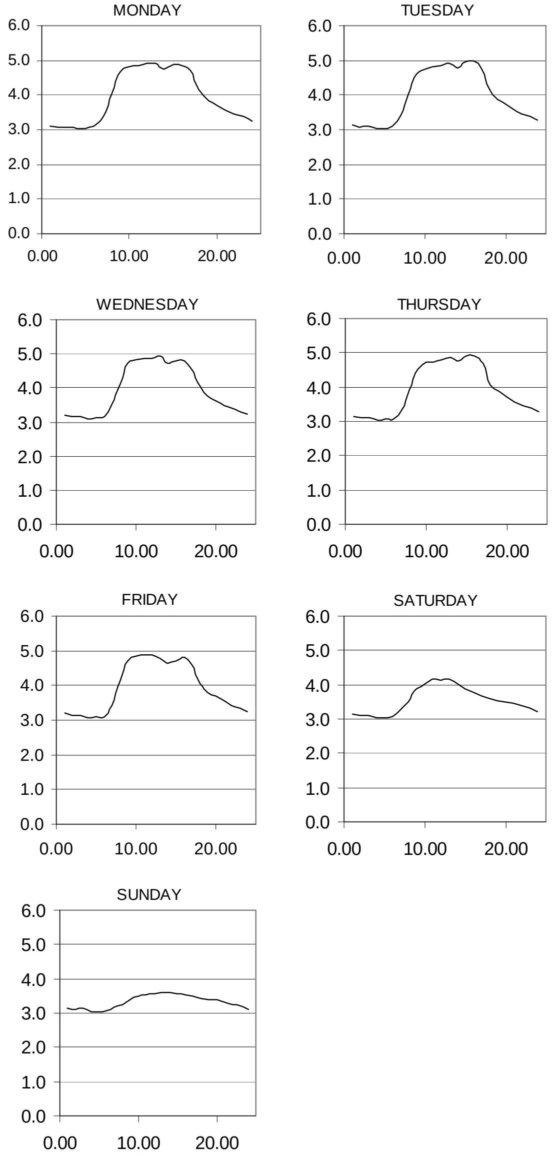

Figure 1. A week of hourly load for a typical hospital in Malaysia

Deriving the representative loads depends greatly on the understanding of the facility load behavior that usually related to the climatic changes. In Malaysia, there is no drastic climatic change all year round. Therefore, it is fair to conclude that the climate will not affect the load behavior very much. Hence, a typical week chronological hourly load could be represented as the annual load characteristic.

However, this representation of annual load will be affected by the two major activities. Firstly, major changes in work operation for example changing from two shift operation to three shift operation or changing policy on working hours etc. Secondly, major expansion of the facility that results in major changes in the load demand will change the amount of energy consumption.

Any of these happens then the design will have to be reviewed.

The study analyses a two months half-hourly load sample of five state and private hospitals in Peninsular Malaysia. As expected, since they are in similar business their chronological load pattern are found to be similar. Based on the data, a typical (standard) hospital weekly chronological load is derived. Figure 1 shows the Monday to Sunday typical chronological hourly load for a hospital in Malaysia that have been derived. It has a high base load of more than 60% of the peak. Its load shapes for Monday to Friday are almost similar while Saturday and Sunday shows a much lower peak due to the absent of the facility administrative load.

The maximum demand of the hospital in Malaysia is between 2 to 5 MW. Largest hospital has 5 MW maximum demands while the smaller hospital is 2 MW. This paper will simulate both hospitals with the 5 MW and 2 MW demand.

3. Generator Model

Five different sizes of generators are modeled. Each generator size has its own thermal efficiency characteristic and therefore it has to be model separately. Table 1a shows the manufacturer specifications of the five turbo generators operated at the maximum loading and temperature 30^{o} C.

The thermal efficiencies vary with loading level. Therefore, it has to be model in order to ascertain a more accurate presentation of thermal output. Based on the manufacturer data of thermal efficiencies at different loading level, it is found that this characteristic is almost a straight-line function as shown in figure 2. For simplicity in the modeling, a straight-line function is used to represent the curves. A linear regression method is used to derive the straight line function. Two factors i.e. the gradient (m) and the constant (c) are defined.

$$\eta_T = mE^{'} + c \qquad (1)$$

where η_T is the thermal efficiency to be calculated at the loading level E' (% loading). Table 1b shows the value of m and c for each generator.

Table 1a
Manufacturers specification of the turbo generator

Turbo Generator	A	B	C	D	E
Electrical Output (kWe)	509	1,226	2,409	4,400	5,640
Electrical Efficiency (%)	17.3	22.2	21.8	27.1	28.7
Heat Recovery Efficiency (%)	57.5	55.9	56	55.1	50.4
Overall Efficiency %)	74.8	78.1	77.8	82.3	79.1
Losses (%)	25.2	21.9	22.2	17.7	20.9

Table 1b
Generator Thermal Characteristics

Generator Thermal Characteristic Variables					
Generator	A	B	C	D	E
Heat Efficiency Gradient (m)	0.248	0.25	0.266	0.238	0.248
Constant (c)	32.7	30.9	29.4	31.3	25.6

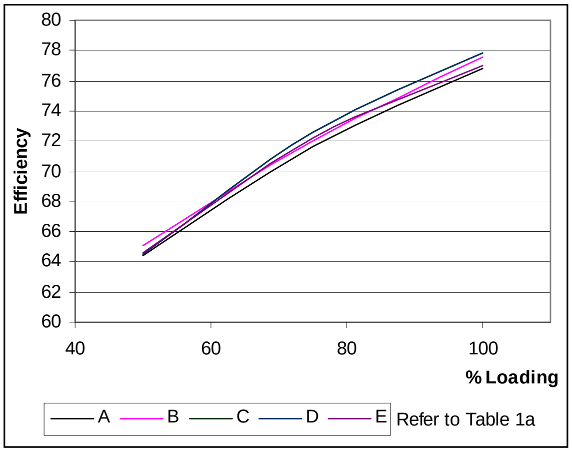

Figure 2. Thermal efficiency at various loading level of a turbo generator

4. Cogeneration System Modeling

The model developed uses gas turbine cogeneration system. This system is most widely used, because the simple cycle gas turbine engine is known to feature: relatively low capital cost, high flexibility, high reliability without complexity [5], short delivery, early commissioning and commercial operation, and fast starting and loading [6][7]. Furthermore, in Malaysia, as a natural producer of gas and having gas pipelines across the country, makes gas turbine to be a better choice. In addition handling the fuel logistic is not as complex as other fuel source such as coal or other renewable energy resources.

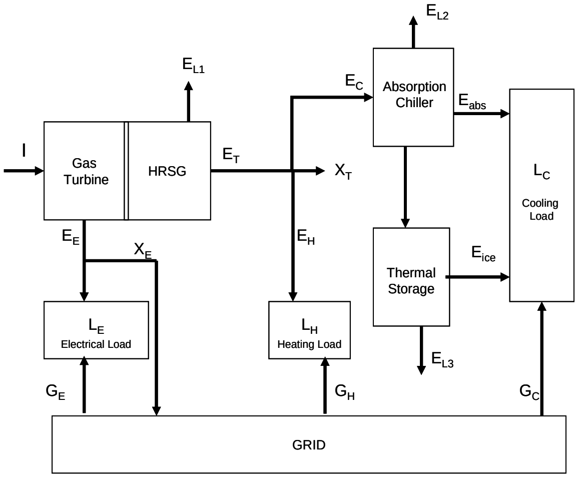

Figure 3. Cogeneration optimization model

Besides the gas turbine, other component involved is the heat recovery system generator (HRSG). Manufacturers of cogeneration system usually designed HRSG together with the gas turbine. In this case, the system specifications provided by the manufacturer will be used especially on the electrical and thermal efficiency, heat recovery rate and losses.

Absorption chiller is another component associated with cogeneration system that uses heat for cooling. This component uses instantaneous recovered heat to cool the instantaneous cooling load. For cases that at the time of heat recovered and there is no cooling load, then it is possible to store the heat to be used when there is a need for cooling load. For this purpose, thermal storage system could be employed to perform he function. Hence thermal storage system is also included in the model. Figure 3 shows the components involved in the model.

The entire component in the model will be involved in energy balance exercise during the simulation. The thermal storage and the energy from the utility are engaged in the load matching process. All the energy balance will be equated to monetary terms, which will be simulated in the optimization exercise.

5. Optimization Model

Based on the cogeneration configuration shown in figure 3, the optimization constraint functions are as follows:

- The electrical output from the turbo generator;

$$I(j) = \frac{m}{\eta_E E_{\max}} E_E^2(j) + \frac{c}{\eta_E} E_E(j) + E_{L1}(j) \qquad (2)$$

It is assumed that η_E is constant at any generator loading. The value of $E_E(j)$ is limited by the maximum capacity $E_{\max}$.

$$0 \le E_E(j) \le E_{\max} \qquad (3)$$

- Electrical load;

$$L_E(j) = E_E(j) + G_E(j) \qquad (4)$$

- Heating load;

$$L_H(j) = E_H(j) + G_H(j) \qquad (5)$$

- Cooling load;

$$L_C(j) = E_{ice}(j) + E_{abs}(j) + G_C(j) \qquad (6)$$

The value of $G_E(j)$ can be positive or negative to represent toping up or exporting of electrical energy. On the other hand the value of $G_H(j)$ and $G_C(j)$ are always more than zero.

The optimization cost function to be minimized is as follows;

$$C = \sum^{week} I(j)*r_1 + \sum^{week} G_P(j)*r_2 + \sum^{week} G_{OP}(j)*r_3$$

$$+ \sum^{week} W(j)*r_4 + \sum^{week} \frac{D_{tu}}{4}*r_5 + \sum^{week} \frac{D_{sby}}{4}*r_6$$

$$- \sum^{week} X_E(j)*r_7 \qquad (7)$$

The top up and standby maximum demand charge are monthly value therefore it is assumed that the weekly values are equally proportioned i.e. divided by four.

The optimum weekly operational cost is found by minimizing the cost function given by (7) subject to equations (2),(3),(4),(5) and (6). Following that, the annual cost is then determined by repeating the values by 52 i.e. extrapolating to annual values. The annual optimum cost plus the annual operation cost is then compared to the utility cost function shown by equation (9).

$$\text{Savings, } \sigma = U - (C*52 + O\,\&\,M) \qquad (8)$$

where *O&M* cost is 10% of the total capital cost per year. It is assumed that the operation and maintenance (major and minor) cost is equal to the total capital cost over the period of 10 years and disbursed the amount over the period.

$$U = \sum^{annual} U_P * s_1 + \sum^{annual} U_{OP} * s_2 + \sum_1^{12} D * s_3 \qquad (9)$$

6. Optimization Solution

As can be deduced from the models the energy balance constraint functions are non-linear. In addition, there are discrete variables in the models. They are the generator size and the minimum generation which can either be a minimum or zero which means switching off the turbo-generator.

In this paper five available sizes of gas turbine is used i.e. 509 kW, 1226 kW, 2409 kW, 4440 kW and 5640 kW will be used. Each machine has its own thermal rate characteristic, which varies with the generator output, and therefore the optimization procedure has to be performed using a machine at a time. The choices of the machine are done based on heuristic basis. A facility with a total of 1 MW peak load (electrical and thermal) will obviously be not optimum to use 5 MW machine. Therefore, at each site we can logically decide that only about three sizes of generator to be used, i.e. about 10% of the total load, 25% of and 50%. Furthermore, for reliability purposes a site may require two sets of equal-sized machine. Therefore, the combination of different choices of generator sizes to be used in the optimization model is limited to 6 combinations. There is no necessity for us to use a conventional integer programming such as branch and bound to enumerate feasible continuous sub-problems of the optimization problem, with regard to generator size. Once the six possible combinations have been determined the problems are solved with each combination with fixed generator size and number of sets. As for the minimum generation, we will solve the problem with a minimum of zero output, i.e. a continuous problem. In other words, we have relaxed the integer variables.

After solving the continuous problem and the results contain some generation outputs which are less than the minimum generation we need to apply integer-programming technique to decide optimally on how to make these output feasible, i.e. set the generator to its minimum generation or switch it off.

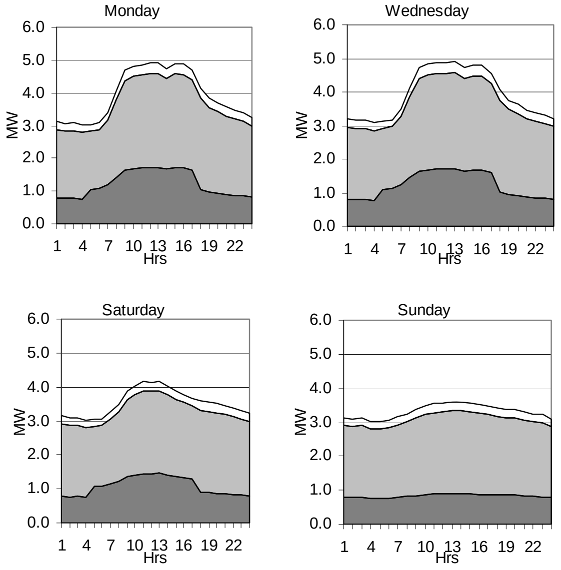

Figure 4. Electrical, Cooling and Heating Load profile

As it turned out in this study all the generator hourly outputs are at the minimum about 80% of the maximum generation capacity. Therefore, we did not have to solve further integer programming problems. Integer programming problem will arise when the off-peak load are too low. This naturally arises in sites such as office and shopping complexes or commercial buildings where the night load is almost zero.

The continuous sub-problems are solved by using two optimization techniques i.e. Newton Raphson and Conjugate using tangent estimates and forward derivatives techniques.

The optimization model will determine the best energy balance between each cogeneration components including the absorption chiller, thermal storage component and the utility top up to achieve the optimum saving. Generator hourly output from Monday to Sunday will be varied to search for the optimum saving.

The energy balances from each component are converted to monetary value. The optimization model will rebalance the energy (by changing the energy input i.e. changing the loading of the generator) to searched for the optimum savings. The optimum saving is calculated by comparing the overall cogeneration cost to the cost if the facility is wholly supplied by the utility.

The feasibility of a cogeneration system is basically dictated by two major factors namely internal rate of return (IRR) and payback period. Besides that, other factors that need to be considered are the overall efficiency, annual savings, peak reduction and energy savings. From a cogeneration facility owner the IRR, payback period and annual savings are the key factors. However, from the authority point of view (government) the overall efficiency, peak reduction and energy savings are equally important.

7. Result and Discussion

The cost data that have been used in the optimization simulation are shown Table 2. Figure 4 shows the load profile of the electrical, cooling and heating load for Monday, Wednesday, Saturday and Sunday. In this study the absorption Chiller COP of 1 is used while thermal storage with losses of 10% is assumed.

Initial optimization involves a heuristic integer programming in selection of the generators. Since the maximum demand is 5 MW only generators type A, B and C were selected. Generator that has capacity more than C unable to gives better result. In hospital load curve, the off-peak is quite substantial and therefore in this case the minimum hourly generator is of 80% of maximum capacity. Both Newton Raphson and conjugate gradient methods achieved a very similar set of results.

Table 2
Cost data

Peak Energy Charge	0.234	rm/kWh
Off-Peak Energy Charge	0.144	rm/kWh
Top Up Energy Charge	0.234	rm/kWh
Demand Charge	19.50	rm/kW
Top Up Demand Charge	19.50	rm/kW
Standby Charge	28.00	rm/kW
Energy Purchase Charge	0.04	rm/kWh
Fuel Cost	12.87	rm/mmbtu
Capital Cost	5,600	rm/kW
Water Rate	1.90	rm/m^3
Ice Storage System	1,200	rm/kW
Ice Storage System Loss	10.00	%
Interest Rate	8.50	%
Inflation rate	8.50	%
Loan (% of total capital)	70	%

Table 3 shows the result of the optimization simulation for 2 MW and 5 MW respectively. The optimization output shows that significant saving as well as optimum efficiency could be achieved by having the right level of generator output (hourly generator output is the variable in the optimization process). For the case of maximum demand of 5 MW both machine 509 kW and 1226 kW could be employed as having a positive financial and technical indicator i.e. the IRR, payback period, savings and the efficiency. Machine 2409 kW on the other hand even though having a positive financial indicator and but its efficiency is not up to he desired value (> 70%). Thermal storage is only required if machine 1226 kW is used. Higher capacity machines will not be suitable for the tested facility. For the 2 MW demand facility, the result shows that for the 509 kW machine is financially attractive. Unfortunately, its overall efficiency is below 70% (target level) even though it employed the thermal storage to improve the thermal matching. This means that it might require a lower capacity machines.

8. Conclusion

A cogeneration system for a 5 MW and 2 MW maximum demand of hospital facility has been simulated using a non linear mixed integer optimization programming. The optimization results show that the optimum savings as well as efficiency could be achieved with the right generation output.

The optimization has employed thermal storage to help to improve thermal load matching in order to improve further the overall efficiency.

Hospital facility having a maximum demand of 5 MW could used 509 kW or 1226 kW machine as both gives the positive technical and financial indicator. Smaller facility i.e. 2 MW maximum demands might need much smaller machine as 509 kW machine did not achieve the desired efficiency even though financial indicator is quite attractive. May be reciprocating engines is a better alternative cogeneration system for hospitals with less than 2 MW peak demand.

This model and its solution are for cogeneration facility planning study. For detailed operational planning when the cogeneration plant sizes have been determined, the optimization problem will be similar to single or two generator unit commitment problem which requires the solution of mixed integer non linear programming.

Acknowledgements

The authors thank Universiti Teknologi Malaysia for providing the facilities. Tenaga Nasional Berhad for the support and Tractors Malaysia Berhad for providing feedback and comments.

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Table 3

	Maximum Demand 5 MW			Maximum Demand 2 MW	
Generator Size (kW)	509	1,204	2,409	509	1,204
Payback Period (yrs)	1.49	2.02	3.01	2.59	4.64
Internal Rate of Return (%)	65.00%	45.00%	24.00%	32.00%	4.00%
Benefit Cost Ratio	1.23	1.43	1.26	1.29	1.1
Overall Efficiency (%)	74.80%	73.15%	61.43%	67.07%	59.96%
Fuel Cost	1,129,013	1,905,321	2,320,020	805,020	957,507
O&M Cost	285,040	698,178	908,791	309,611	472,514
Standby Charge	739,456	1,482,854	1,559,477	574,056	661,285
Top Up Demand Charge	650,203	132,480	81,292	82,326	73,747
Top Up Energy Charge	3,250,554	324,931	157,011	223,496	41,515
Water Consumptions	15,444	24,240	24,392	9,742	9,822
Sales of Electricity	0	-40,405	-87,086	-4,899	-40,539
Total Cost With Cogeneration	6,069,710	4,527,599	4,963,897	1,999,352	2,175,851
Total Cost without Cogeneration	7,985,987	7,985,987	7,985,987	3,194,395	3,194,395
Savings	1,916,277	3,458,388	3,022,090	1,195,043	1,018,544