Study on the Effect of a Cogeneration System Capacity on its CO₂ Emissions*

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Abstract

With the global warming problem aggravating and subsequent implementation of the Kyoto Protocol, CO₂ emissions are becoming an important factor when verifying the usability of cogeneration systems. Considering this, the purpose of this work is to study the effect of the capacity of a cogeneration system on its CO₂ emissions under two kinds of operation strategies: one focused on exergetic efficiency and another on running cost. The system meets the demand pattern typical of a hospital in Japan, operating during one year with an average heat-to-power ratio of 1.3. The main equipments of the cogeneration system are: a gas turbine with waste heat boiler, a main boiler and an auxiliary steam turbine. Each of these equipments was characterized with partial load models, and the turbine efficiencies at full load changed according to the system capacity. Still, it was assumed that eventual surplus of electricity generated could be sold. The main results showed that for any of the capacities simulated, an exergetic efficiency-focused operational strategy always resulted in higher CO₂ emissions reduction when compared to the running cost-focused strategy. Furthermore, the amount of reduction in emissions decreased when the system capacity decreased, reaching a value of 1.6% when the system capacity was 33% of the maximum electricity demand with a heat-to-power ratio of 4.1. When the system operated focused on running cost, the economic savings increased with the capacity and reached 42% for a system capacity of 80% of maximum electricity demand and with a heat-to-power ratio of 2.3. In such conditions however, there was an increase in emissions of 8.5%. Still for the same capacity, an exergetic efficiency operation strategy presented the best balance between cost and emissions, generating economic savings of 29% with a decrease in CO₂ emissions of 7.1%. The results found showed the importance of an exergy-focused operational strategy and also indicated that lower capacities resulted in lesser gains of both CO₂ emissions and running cost reduction.

Key words: Simulation, Cogeneration Capacity, CO₂ emissions, Operation Strategy, Exergy

1. Introduction

With the gradual depletion of the world fossil fuel sources and with the global warming problem, high efficiency performance and CO₂ emissions are important parameters to regard in design and operation of power systems. In this field, cogeneration systems already present some advantages related with high efficiency performance, due to its ability to generate power and heat simultaneously. However, eventual benefits regarding CO₂ emissions resulting from the use of cogeneration systems depend on several parameters

*Received 16 Jan., 2008 (No. 08-0031)
[DOI: 10.1299/jpes.2.1178]

such as fuel source, design, and operation strategy. Moreover, some studies have been conducted in Japan trying to characterize the effect of different parameters on cogeneration systems' performance. It is possible to mention, for instance, the research of ^[1], where an economic study was done to find the best number of micro turbine that optimizes a cogeneration system. Another example is ^[2], where two kinds of cogeneration systems were optimized to find the minimal selling price of electricity that would make the systems feasible from the economic point of view.

This study goes further in such characterization, and its purpose is to analyze operation strategies for systems installed in facilities. In this paper the effect of the capacity of a cogeneration system on the system performance and its CO₂ emissions focusing on two kinds of operation strategies were mainly considered. The objectives of the operation strategies were the system's best exergetic efficiency and its minimum running cost. Furthermore, a comparison between each operation strategy was done using a conventional system solution as reference. In this way, the trade-offs involved, as well as possible improvements in cost reduction, efficiency and in CO₂ emissions achieved through operation strategies could also be verified and had their importance assessed.

2. Fundamentals

2.1. System Configuration

The cogeneration system simulated is composed by a gas turbine with a heat recovery system, a boiler, an auxiliary steam turbine, and heating and cooling systems. The system works to meet a demand of heat, cooling and electricity. Steam and electricity are generated by the gas turbine; if the amount of any of these products is not enough to meet their respective demands the lack of steam or power can be supplied from the gas boiler and public grid, respectively. Also, depending on demand conditions, the auxiliary steam turbine is activated, using steam surplus from the gas turbine, and produces electricity to the cooling system operation. The cooling system can be operated with electricity purchased from public grid, or generated by the auxiliary steam turbine. Moreover, the only function of the auxiliary steam turbine is to generate electricity for the cooling system. Finally, it was assumed that eventual electricity surplus produced by the gas turbine could be sold.

The demand pattern that the cogeneration system was supposed to meet is typical for a 20 000 m² hospital in Japan. The data used is available from the Society of Heating, Air Conditioning and Sanitary Engineers of Japan presented in ^[3]. The average heat to power ratio of this demand pattern is 1.3. The data of heat, cooling and electricity of the demand pattern are given for every hour of one typical day per month during one year. Examples of these data are shown on Fig. 1.

The problem studied in this work involved the variation of the capacity of the gas turbine and verifying how the cogeneration system performance, including CO₂ emissions, is affected according to two optimal operation strategies: one focused on the minimal running cost of the system, and another one focused on its best exergetic efficiency. For each gas turbine capacity, a simulation was done and the optimal operation strategies for both objectives studied were determined

Fig. 1 Four months of the simulated demand pattern

2.2. Equipments Characterization

To enable efficiency variation in part-load operation, the auxiliary steam turbine, gas turbine, and boiler were characterized with partial load models available in [4]. The compressor was modeled with a head versus flow curve and the remaining equipments were modeled using mass and energy balance equations. The following is a brief description of the gas turbine and boiler models.

In Eq. (1), Eq. (2) and Eq. (3) the gas turbine model is presented.

$$W_{gtb} = n_{gtb} \cdot m - W_{gtb,int} \quad (1)$$

$$n_{gtb} = \frac{L+1}{B_{gtb}} \cdot \left(NHV - \frac{A_{gtb}}{m_{max}} \right) \quad (2)$$

$$W_{gtb,int} = \frac{L}{B_{gtb}} \cdot (NHV \cdot m_{max} - A_{gtb}) \quad (3)$$

The coefficients A_{gtb} (kW) and B_{gtb} represent the relationship between the power W_{gtb} (kW) and the heat flow from fuel combustion. In this study, the values A_{gtb} and B_{gtb} were obtained from the curves presented by [5]. The parameters n_{gtb} (kW/kg) and $W_{gtb,int}$ (kW) are the slope and intercept of Eq. (1), respectively, and m (kg/s) is the mass flow of fuel. As Eq. (2) and Eq. (3) show, these parameters depend also on the net heat value of the fuel, NHV (kJ/kg), the maximum fuel flow m_{max} (kg/s), and L , called intercept ratio. According to [4], the intercept ratio L depends on several factors as turbine size, manufacturer, application, etc. In this study its value ranged from around 0.4 to 1.6.

The boiler model is described in Eq. (4). This equation relates the boiler's efficiency η_{gb} , with the mass fraction of steam generated $m_{stm,o}$ and pressure variation inside of the boiler, represented by R_{ph} . The boiler model also considers losses created by the blowdown ratio, represented by R_{bd} . Still in Eq. (4), the parameters a and b are regression parameters representing different boiler types and designs. The values for all the parameters presented in Eq. (4) were calculated from the curves presented in [4].

$$\eta_{gb} = \frac{m_{stm,o}}{a + m_{stm,o} \cdot (b+1) + R_{ph} \cdot R_{bd} \cdot m_{stm,o}} \quad (4)$$

Regarding equipment sizing, the gas turbine can operate down to a minimum of 40% of its maximum load. The auxiliary steam turbine was sized according to the maximum amount of steam that can be recovered from the heat recovery system (which receives the gas turbine's exhaustion gases). The cooling system attached to the auxiliary turbine was sized to meet the maximum cooling load. The boiler was sized to produce enough steam to meet the maximum heating and hot water demand of the hospital. Simulations were done with five different values for the maximum capacity of the gas turbine. These values were based on the average of annual electricity demand and its standard deviation. The capacities and efficiencies specifications for the gas turbine and other equipments are presented in Table 1. For the gas turbine both the maximum power and efficiency were changed. For the auxiliary steam turbine, the same maximum efficiency was kept independently of the maximum load.

Table 1 Equipments capacity and efficiency.

Equipment	Capacity (at maximum load)					
Gas turbine system	Heat/Power	4.1	3.3	2.8	2.5	2.3
	Power (kW)	330	450	570 ⁺	690	805
	1 st Law Efficiency [*]	0.15	0.178	0.201	0.22	0.234
Aux. steam turbine	Power (kW)	378	411	443	475	508
	1 st Law Efficiency	0.82 ^{**}				
Compressor	Power input: 672 kW COP: 3.42					
Boiler system	Heat output: 4.05 MW 1 st Law efficiency [*] : 90 %					

^{*} Value based on the fuel LHV

^{**} 1st Law efficiency only of the steam turbine.

⁺ Annual average electricity demand.

2.3. Simulation procedure

In order to simulate the operation of the cogeneration system, the equipments modelled were integrated in a computer program. The optimization procedure was done calculating all feasible operation conditions for every one hour of demand data in which the cogeneration system meets such demand. After that the program locates within these calculated operation conditions the one that maximizes or minimizes the objective of the operation strategy being optimized. Also, for every hour, the solution using the conventional system (boiler and purchased electricity) is calculated, and in case this solution is better than the cogeneration one, the program indicates the conventional system as the best operation strategy for that hour.

One of the objectives optimized was the system exergetic efficiency ε . As Eq. (5) shows, this value was calculated as the ratio of the sum of the product exergy E_P by the fuel exergy E_F , following the methodology available in [6].

$$\varepsilon = \frac{\sum E_P}{\sum E_F} \quad (5)$$

The reference temperature, as well as the ones related with steam production and demand conditions used in the calculations related with exergy are available in Table 2.

Table 2 Input temperature values used in the calculations.

	Reference Condition	Steam Produced	Demand		
			Hot Air	Hot Water	Cooled Air
T (K)	288*	504	303	363	291

*Temperature used as reference in the exergy calculations.

Another objective optimized was the running cost of the system, rc in Eq. (6), assumed as the sum of fuel and electricity costs, C_{fuel} and C_{elec} respectively, less the revenues produced from the selling of eventual surplus of generated electricity S_{elec} . The variables C_{fuel} and C_{elec} are calculated based on their respective unitary costs and on the total amounts of fuel and electricity purchased in every hour including the necessary amount to operate the system auxiliary equipment. The fuel and purchased electricity's unitary costs were set to 37.21 yen/m³ and 12.11 yen/kWh, respectively. Both values are referenced by [2]. The selling price of eventual electricity surplus was assumed to be 4 yen/kWh and this value was also based on the same reference. Construction costs were not regarded in this work as the focus is on operation strategies.

$$rc = C_{fuel} + C_{elec} - S_{elec} \quad (6)$$

Although not an optimization objective, an important parameter was the CO₂ emissions. This value was regarded as the reduction ratio caused by using cogeneration instead of the conventional system throughout the year. The CO₂ emissions of each system were based on their total fuel consumption, and on CO₂ emissions that the electricity purchased by each system generated in its origin. The CO₂ emissions generated by the electricity purchased were calculated using the lifecycle CO₂ emissions index. In this study it was assumed that purchased electricity comes from a natural gas fired power plant; according to [7], for this kind of power plant in Japan, the lifecycle CO₂ emissions value is estimated as 563 gCO₂/kWh.

3. Results

3.1. Best exergetic efficiency operation strategy

The monthly economy in running cost when operating the system to maximize its exergetic efficiency, for all range of gas turbine capacities simulated, is in Fig. 2.

Fig. 2 Monthly economy (compared with the conventional system) for each gas turbine capacity - Best exergetic efficiency operation strategy.

As one can see in Fig. 2, the highest gas turbine capacity produced the highest economy achieved in running cost. Especially in winter and summer, the system with the highest capacity (80% of maximum electricity demand, heat to power ratio of 2.3) produced an economy that was about twice as large as the system with the smallest capacity. In spring, the effect of capacity on the monthly economy was not significant as the heat demand gradually decreased reducing the advantage of cogeneration. The simulation program calculated the best solution, including the conventional system solution, so, when the value of the best exergetic efficiency found is the same as the conventional system, it means that

there is no operation strategy using cogeneration that would result in an exergetic efficiency better than the one obtained using the conventional system.

Figure 3 shows the values for the best exergetic efficiency operation strategy using the conventional system, and using the cogeneration system changing the gas turbine capacity. Increasing the cogeneration system capacity also improved the exergetic efficiency, and in the same months where the best economy values were achieved, there were the best exergetic efficiencies. In this case, it is clear that whenever it was possible to improve the exergetic efficiency, in relation to the conventional system, the economy also improved.

Fig. 3 Exergetic efficiency through out the year for each gas turbine capacity - Best exergetic efficiency operation strategy.

Analyzing the CO₂ emissions reduction compared with the case where the conventional system is used to meet the demand (Fig. 4), there was a similar behavior to the economy item in Fig. 2. The best values of reductions in emissions were also achieved in winter and summer. However, while the economy item had its maximum monthly value located in a summer month, the highest reduction in CO₂ emissions was achieved in winter.

Fig. 4 CO₂ emissions through out a year for each gas turbine capacity – Best exergetic efficiency operation strategy.

3.2. Minimum running cost operation Strategy

The monthly economy achieved using cogeneration with an operation strategy that minimizes the running cost is on Fig. 5. In this case, a monthly economy over 30%, compared with the conventional system, was found in almost all months of the year, even in periods when the heat demand was not high. Also, the highest capacity continued to be the one in which the best values of economy were generated.

Fig. 5 Monthly economy (compared with the conventional system) for each gas turbine capacity – Minimum running cost operation strategy.

The effect of minimizing the running cost on exergetic efficiency is shown on Fig. 6.

Fig. 6 Exergetic efficiency in one year for each gas turbine capacity - Minimum running cost operation strategy.

The cogeneration capacity did not have a clear trend related with the exergetic efficiency as in summer the system with the highest capacity had the worst exergetic efficiency. Another point is the consequence of minimizing the running cost. In all months of the year, with any capacity, the system operated with exergetic efficiency lower than the conventional system one.

For the CO₂ emissions reduction, the effect of minimizing the running cost was negative, as Fig. 7 shows. Only in four months of the year, there was reduction in emissions; in the other months there was an increase of over 10% in emissions most of the time.

Fig. 7 CO₂ emissions through out the year for each gas turbine capacity - Minimum running cost operation strategy.

3.3. Results Discussion

Fig. 3 and Fig. 6 show that the differences in exergetic efficiency between operations strategies studied were significant. The exergetic efficiency for the minimum running cost strategy was usually lower than the one of the conventional system. To understand this behavior, the exergy of the cogeneration system operating in the 11th hour (11:00 am) of a typical day in May and in August are shown for the maximum gas turbine capacity studied. May and August were chosen because during these months, one of the highest and one of the lowest exergetic efficiency values were reached for the minimum cost strategy. Moreover, the time 11:00 am was selected because the cogeneration system was operating at full load at this time. The demand for these hours is in Table 3 and their respective exergy distributions in Fig. 8 (a) and (b).

Table 3 Demand conditions for 11th hour of a typical day in May and August.

	May	August
Electricity Demand (Wh)	8.01 E+05	1.00E+06
Cooling Demand (Wh)	8.88 E+04	2.00E+06
Heating Demand (Wh)	0	0
Hot Water Demand (Wh)	7.16E+05	5.02E+05

In May the gas turbine was used to supply almost all the electricity demand for the cost minimization strategy. Also, all the heat demand needed was supplied by the heat recovery system, what resulted in boiler deactivation. In spite of that, it is possible to see in Fig. 8(a) that a great amount of heat recovered was not used and as a consequence a considerable amount of exergy was lost. This fact results from getting all the electricity needed from the gas turbine, in which cheap electricity was generated, but at the same time waste of available heat in the exhaustion gases due to lack of demand for it. This contributed to a low exergetic efficiency.

Fig.8 Comparison in exergy use in the cogeneration system in a given hour between operation strategies.

For the same 11th hour of a typical day in May, the best exergetic efficiency strategy had a different approach than the previous one. In order to maximize the exergetic efficiency, the gas turbine load was decreased to the amount in which all the heat recovered from its exhaustion gases is used. As this load is low, all the electricity needed was not generated by the gas turbine and a considerable amount was purchased from the public grid as Fig. 8(a) shows. In this way, exergy efficiency was improved, as the gas turbine generated enough electricity and heat to deactivate the boiler. At the same time the running cost decreased as the amount of purchased electricity decreased.

In August the irreversibilities in the minimum running cost strategy were higher again than the best exergy strategy but this time for a different reason. For the minimum running cost solution, it was purchased only the amount of electricity necessary to meet the electricity demand (in this hour it had a higher value than the maximum production of the gas turbine), and to meet part of the cooling demand (the auxiliary steam turbine output was not enough to meet it). Also, in this operation strategy, both boiler and gas turbine were used and the cogeneration system had exergetic efficiency slightly lower than the one of the conventional system, as shown in Fig. 3. The reason is in the higher utilization of the boiler and auxiliary steam turbine.

Analyzing the best exergetic efficiency strategy results for the 11th hour of August in Fig. 8(b), it is possible to note that the gas turbine was also used at a high operation load. Nevertheless, the boiler was deactivated, the auxiliary steam turbine used only heat recovered from the gas turbine, and the remaining amount of energy needed for cooling and electricity demands was provided from the public grid. Moreover, the reduction in the auxiliary steam turbine load indicated the effect of the deactivation of the boiler, explaining also why more electricity was purchased compared with the minimum running cost solution (the difference in the electricity amount purchased in the best exergy efficiency strategy was to supply the cooling demand). In this way, the best exergetic efficiency was achieved.

In Fig. 9 there are the annual CO₂ emissions and average utilization load of the main equipments for each gas turbine simulated capacity. For the running cost optimization, the gas turbine was highly used, resulting in savings on the boiler fuel costs and purchased electricity expenses, as well as in income from electricity sold. Nonetheless, the consequence of such use of the gas turbine was the increase in CO₂ emissions as shown in Fig. 7. Also, increasing the capacity of the gas turbine, at first led to a higher utilization of

it, as its efficiency at part-load operation also improved. If the capacity becomes too high, however, there is a smaller ability to use the gas turbine when the demand is small (the gas turbine minimum load of 40% of its maximum capacity varies in the same way) and its average use decrease, resulting in a slight decrease in emissions too.

Fig. 9 CO₂ emissions and equipment average load during one year according to different gas turbine capacity and operation strategy objective.

In case of the exergy optimization shown in Fig. 9, a balance between gas turbine, boiler and purchased electricity was searched. In this strategy the gas turbine was used only when it was justifiable from the exergy point of view, and the result was a gradual replacement of purchased electricity by the one generated by the gas turbine, according to the increase of its capacity.

Operating the system to maximize the exergetic efficiency decreased the system CO₂ emissions and also provided reasonable economy (in the months where the demand justified the use of cogeneration from the exergy point of view). Table 4 shows the differences between the optimization strategies according to the gas turbine capacities simulated.

Table 4 Annual results of the performance variables according to gas turbine's capacity and operation strategy.

Optimization Objective	Exergetic Efficiency (Minimal Running Cost)		
	Average Exergetic Efficiency	Economy*	Annual CO ₂ Emissions Reduction*
0.33x	0.243	7.1%	1.6%
	(0.2081)	(17.8%)	(-12.3%)
0.45x	0.246	12%	3%
	(0.211)	(25.2%)	(-10.2%)
0.57x ⁺⁺	0.25	21.4%	4.5%
	(0.194)	(31.8%)	(-12.6)
0.69x	0.253	26.2%	5.9%
	(0.192)	(37.8%)	(-11.1%)
0.80x	0.257	29%	7.1%
	(0.196)	(42.4%)	(-8.5%)

* Value in percentage using the conventional system as reference.

⁺⁺ Annual average electricity demand

x: Maximum electricity demand

The highest capacity value simulated resulted in the best values for both minimum running cost and exergetic efficiency optimizations, and the trade-offs between these strategies are clear. In the minimum running cost strategy an economy of 42.4% in running cost caused an increase of 8.5% in CO₂ emissions, whereas in the best exergetic efficiency

operation strategy there was a scenario where an economy of 29% was reached with a decrease of 7% in CO₂ emissions.

4. Conclusions

The purpose of this work was to verify the impact of a cogeneration system capacity on the system performance and its CO₂ emissions, focusing on two kinds of operation strategies. The results found indicated that the best capacity simulated was the one corresponding to a gas turbine capacity equivalent to 80% of maximum electricity demand. This fact was true for both minimum running cost and best exergetic efficiency operation strategies. Also, the cogeneration system exergetic efficiency was an interesting variable to be considered when optimizing the simulated system operation, as it produced both economy and decrease in CO₂ emissions when compared with the conventional system. On the other hand, the pure minimization of the running cost generated higher economy at the expense of more CO₂ emissions. Finally, the comparison between different operation strategies showed their importance, as it indicated that for systems already installed and under operation there is space for further reduction in CO₂ emissions through operation strategy adjustments. More investigation should be done with other demand patterns in order to verify if this behavior represents a general trend or not.

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