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Fuel Energy Saving and Environmental Benefits from a Combined Heat, Cooling and Power System Driven by Gas Engine

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ABSTRACT

One of the local power generation resources that is attractive for investors due to its high efficiency and reduction of input fuel consumption is trigeneration system. The utilization of these systems is possible by using different strategies. Three kinds of such strategies which are electrical dispatch, thermal dispatch and hybrid dispatch have been used in this study. At first, several indices of utilization such as overall energy saving, thermal efficiency and energy-chargeable-to-power are computed in each one of these strategies and then compared together. In addition, the index of CO_2 gas emission is evaluated in each utilization strategy as well as in case of without CHP and their results are compared together.

Key words: Cogeneration, emission reduction, fuel energy saving, greenhouse gases, micro Turbinem, trigeneration

INTRODUCTION

There has been a growing dispersion of several small scale technologies with electrical rated power below (1MWe) for DG in recent years. Cogeneration and trigeneration systems, as a result of their improved energy performance, can also bring important advantages in terms of GHG emission reduction with regards to the SP. This may happen especially in those countries where electricity production mainly depends on non-renewable resources.

Generation of electricity and heat that usually is in the form of steam and/or hot water is simultaneously done in a CHP system. Cogeneration systems are able to meet the needs of various small-scale users such as restaurants, hospitals, universities, shopping malls, hotels and so on (Chicco and Mancarella, 2008; Wu and Rosen, 1999).

From this point of view, the advantages which are provided by DG in the electricity section (Borbely and Kreider, 2001) can be extended to cause the local production of cooling and heat power by means of modernized machines that can be effectively integrated with conventional generation systems (Chicco and Mancarella, 2007). Actually, technologies such as the MT and the ICE are being used well in co-generation of heat and electricity which can bring considerable economic benefits and energy saving compared with the SP of the same energy vectors so that electricity and heat are generated in the centralized power system and local boilers, respectively (Horlock, 1997; Martens, 1998).

It is possible to achieve overall trigeneration efficiencies (based on the electrical, thermal and cooling energy products) of over 80%. As compared with other systems which generate thermal, cooling and electrical energy separately, other advantages of trigeneration system include:

- Energy consumption reduction
- Environmental emissions reduction
- More reliable, safe and economic operation

The type and size of a trigeneration system are normally chosen to match as optimally as possible the thermal, cooling and electrical demands. CHP systems can be designed to follow the electrical or thermal loads (electrical and thermal dispatch) or to satisfy the electrical or thermal base-loads (Rosen, 1998; MacLaren Engineers Inc., 1988).

Compared to the production of electric, cooling and thermal energy in separate systems, energy savings can reach 15-40% of primary energy need by using CHP or CHCP systems. Cogeneration causes reduction of greenhouse gases and CO_2 emission, avoiding transmission loss while gaurantying high quality power supply and giving lower capital expenditure in electric energy transmission grid capacity (Panno *et al.*, 2007). Therefore, cogeneration is an economically reasonable method for environmental improvement, the conservation of resources and financial benefits (Najjar, 2000; Eastop and Mcconkey, 1993).

In this study, in order to find the energy consumption characteristics of the CHCP system and to show the technological and economical advantages, a typical CHP setup has been analyzed and the fuel saving rate and CO_2 generation for different operating conditions has been evaluated.

GREENHOUSE GASES EMISSION

One of the sources causing the emission of GHGs is the energy sector. By converting chemical energy in fossil fuels into appropriate energy such as electricity and thermal processes, a wide variety of emissions and by-products are created. Considering this conversion process leads to figure out this fact that it is vital to conserve energy and prevent these emissions from being generated in the first place. Increase in the amount of carbon dioxide is an important factor in green house effect which increases the probability of the earth heating and regional changes. Table 1 shows CO_2 emissions from some power generation plants.

There are some simple and varied solutions to prevent and reduce emissions. The most important and effective solution is conservation measures which reduce the total amount of energy generated and used, decreasing all GHGs and pollutants. By considering this fact that combustion of fossil fuels inheritably produces an amount of carbon dioxide, it can be concluded that a reduction of fuel input leads to reductions in CO_2 outputs and mass of toxics. Some air pollution emissions from some power generation plants are given in Table 2.

As we can see in Table 1 and 2, the reduction of fuel input decreases contaminant and greenhouse gas output. Since CHP system causes lower energy consumption and produces two or

Table 1: Comparison of CO_2 emissions from various power generation plants

Type of power generation plant	CO_2 (kg MWh^{-1})
Coal	1000
Oil	790
Gas	560
GTCC	355
GTCHP	236
Biomass	0
IGCC	740

Table 2: Comparison of air pollution emissions from various new energy generating plants

Type of power generation plant	SO_2 (kg MWh^{-1})	NO_X (kg MWh^{-1})	PM (kg MWh^{-1})
Coal	25.00	2.0	0.50
Oil	1.90	1.5	0.50
Gas	0.00	1.0	0.00
GTCC	0.00	0.4	0.00
GTCHP	0.00	0.2	0.00
Biomass	0.25	0.6	0.40
IGCC	0.25	0.5	0.15

three useful forms of energy from one fuel source, a practical example of energy efficiency and reduction of GHGs is CHP system (Villarroel and Klein, 2006).

STRATEGIES OF CHP UTILIZATION

There are several ways to utilize a CHP system and each of them has its own advantages and drawbacks.

Electrical dispatch: One way to operate cogeneration is that the amount of required electricity takes the first priority and heat produce has the second priority.

In this case, capacity magnitude of cogeneration system power produce is determined as maximum required electricity load. Then, the supplied heat is compared with heat demand and in case of shortage of heat production; boiler will enter the circuit and run. Certainly, in this strategy there is not any excessive power to be sold to the network.

If the need to local electricity goes beyond the rated CHP power, the remaining required power would be purchased from the network. It is possible that a lot of energy and input fuel be wasted as heat in some hours that the electrical consumption is high and the thermal consumption is low. This strategy has been shown for an hour in Fig. 1. It is clear that this process for a day should be repeated twenty four times.

Thermal dispatch: This approach is exactly the opposite of first method because in this approach the first priority is required heat produce and power produce takes second priority. In this approach if power required to supply the heating need exceeds unit rated power, boiler will be run. So certainly in this case excessive heat which can be used to produce cool, is not supplied by unit and it is necessary to use site chiller to satisfy the cooling needs. So, its required power is provided by unit from excessive generated power and otherwise, it is purchased from network. In this situation in case of power shortage, it is possible to purchase more required power from network. There is a situation in which excessive power is produced by the unit to supply heat needs. This excessive power can be used to run site chiller (if it is required) and then its excessive is sold to the network. Flowchart of thermal dispatch is similar to Fig. 1 except that the start point is thermal demand, the possibility of power sale to the network exists and the term P_{c2} is added with a negative sign to the objective function.

Hybrid strategy: In this method, the best state of operation and usage of CHP is chosen and trigeneration produce is done according to that choice. In this algorithm, CHCP rated power is chosen as start point. Then considering generated heat and comparing to heat demand at that time, it is determined that boiler operates or not. In case of cooling demand, this need is supplied by

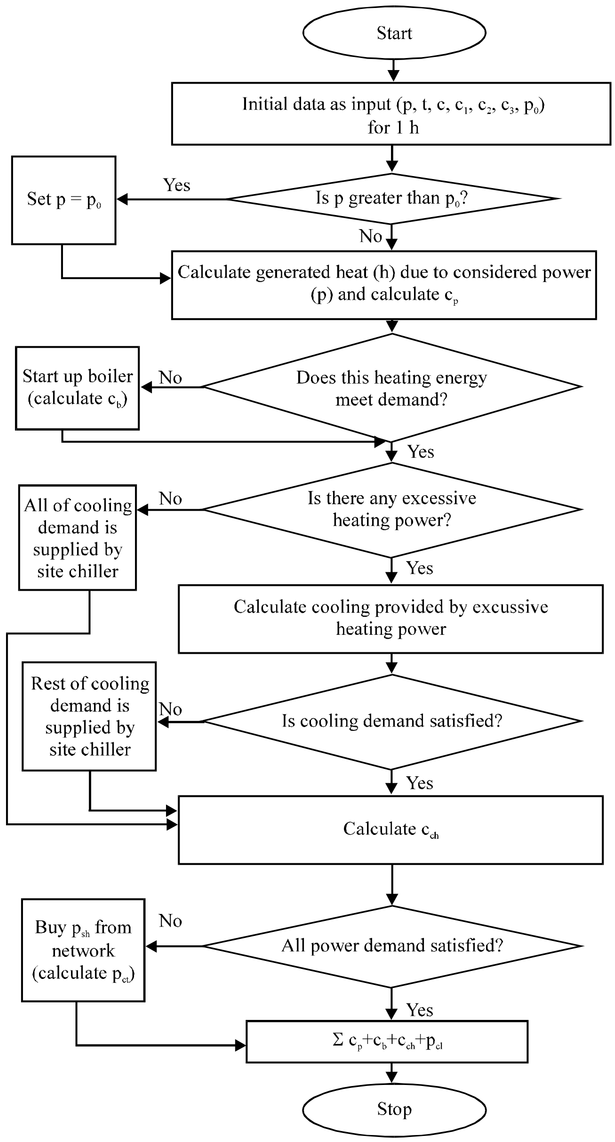

Fig. 1: Flowchart of electrical dispatch for 1 h

excessive generated heat (if it is available). If this heat could not fulfill cooling need, it is necessary to run site chiller. Required power for site chiller is first supplied by excessive power generated by unit (if it is available) and then by network. Finally, if generated power could not supply need of consumer, the remaining power is purchased from network. If there exists any power produced by unit, it is first used in cooling process and the remaining power is sold to the network. In this strategy, the whole possible states of unit power, heat and cooling produce are investigated and finally the one with less cost is introduces as the optimal state.

The objective function is defined to minimize the investment's costs as below:

$$\text{Min} \sum C_{\text{engine and boiler fuel}} + C_{\text{electricity import}} - P_{\text{sale of additional power}} \tag{1}$$

It can also be written as following:

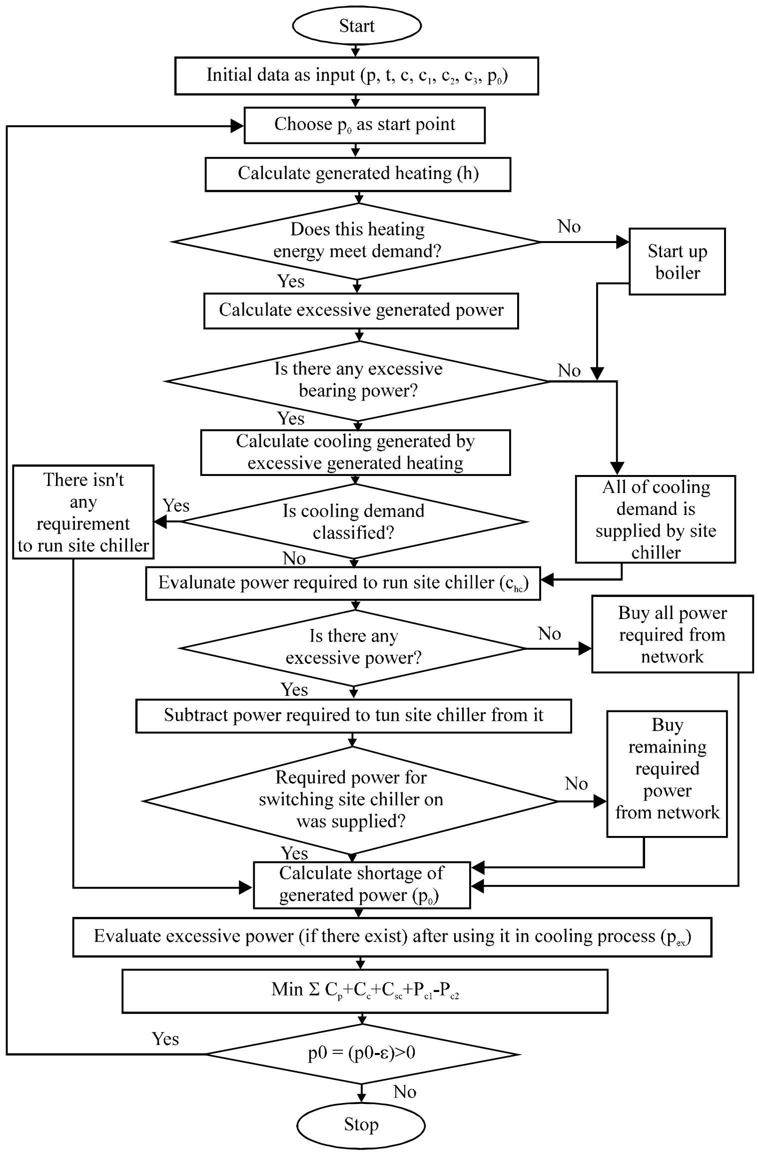

Fig. 2: Flowchart of hybrid dispatch for 1 h

$$\text{Min}\sum C_P + C_b + P_{C1} - P_{C2} \tag{2}$$

Subject to $P_{chp}<P_0$: Principles of simulation are in a way that values of consumer's power and heat need along with price of network power at that time and sale price of distributed generation unit power are received by optimizer in each time interval. This strategy is shown in Fig. 2.

EFFICIENCY OF COGENERATION PLANT

With the reduction in fossil fuel resources and consequently getting expensive and also considering available concerns in the pollution of environment about using these fuels, the usage of renewable generations has been increased. On the other hand, raising the efficiency of the available systems and the maximum use of these fuels are the other solutions to the mentioned problems. Cogeneration systems has been growing because of the increase in utilization of fuel and raising the usage efficiency of their input energy.

Thermal efficiency: The simplest approach to describing the efficiency of a cogeneration plant is to simply divide the total output energy (electrical plus thermal) by the total thermal input, remembering to use the same units for each quantity:

$$\text{Overall energy efficiency} = \frac{\text{Electrical output} + \text{Thermal output}}{\text{Thermal input}} \times 100 \tag{3}$$

Overall energy saving: A better way to evaluate CHP is by comparing the cogeneration of heat and power, in the same unit, to generation of electricity in one unit plus a separate boiler to provide the equivalent amount of heat. This method, however, requires an estimate of the efficiency of the separate boiler. There are several ways to capture this concept. One approach is to compare the overall thermal efficiency represented by Eq. 3, with and without cogeneration:

$$\text{Overall energy saving} = 1 - \frac{\text{Thermal input with CHP}}{\text{Thermal output without CHP}} \times 100 \tag{4}$$

The improvement can be easily determined by the following Equation.

Energy-chargeable-to-power: Under the assumption that the facility needs heat anyway, say for process steam, the extra thermal input needed to generate electricity using cogeneration can be described using a quantity called the ECP as following:

$$\text{ECP} = \frac{\text{Total thermal input} - \text{Displaced thermal input}}{\text{Electrical output}} \tag{5}$$

In this equation, the displaced thermal input is based on the efficiency of the boiler if one had been used. The units of ECP are the same as power plant which is Btu kWh^{-1} or kJ kWh^{-1}. The ECP depends on the amount of usable heat recovered as well as the efficiency of the boiler that would have generated the heat had it been provided separately.

Cost chargeable to power: When the ECP is modified to account for the cost of fuel, a simple measure of the added cost of electricity with cogeneration, called the operating CCP, can be found from Eq. 6. CCP will have units of \$ kWh^{-1}.

$$\text{CCP} = \text{ECP} \times \text{Unit cost of energy} \tag{6}$$

Numerical study: In this part of the study, a cogeneration system is considered in which the required electrical and thermal loads over a day are varying as shown in Fig. 3.

As it is observable, the thermal demand at hours 0-10 and 19-24 is more than electrical demand but in the middle of the day when the weather gets warmer, the amount of electrical consumption

Table 3: Data used in simulation

Parameter	Value
P_0	400 Kw
η_h	50%
η_p	40%
η_n	33%
η_t	75%
η_{ab}	22%
COP_{CHCP}	0.7
$COP_{\text{site chiller}}$	3.33

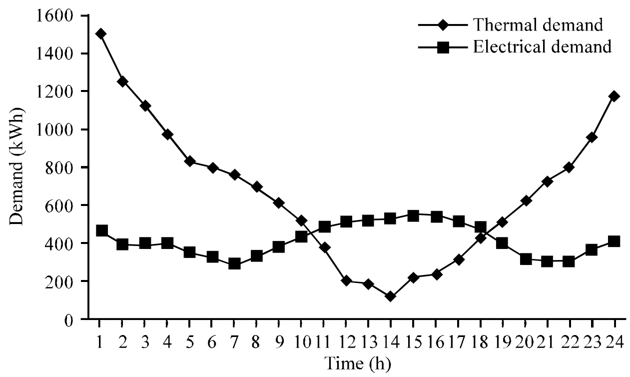

Fig. 3: Electrical and heating load profile

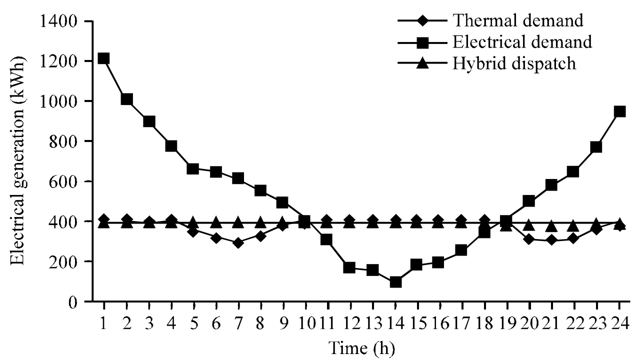

Fig. 4: Electrical output

would be greater than thermal consumption. The features of CHP as well as boiler are given in Table 3.

The utilization of CHP by using three proposed strategies in the first part has been studied. Fig. 4 and 5 show electrical and thermal outputs of a CHP system, respectively.

As it is can be seen, CHP generation is different in various strategies. So, it is expected that the amount of CO_2 production and also the Overall Thermal Efficiency (OTE) and the Overall Energy Saving are different. Therefore, considering the goal and purpose of CHP system utilization as well as available economical limitations, the operator should choose the appropriate strategy and utilize the system.

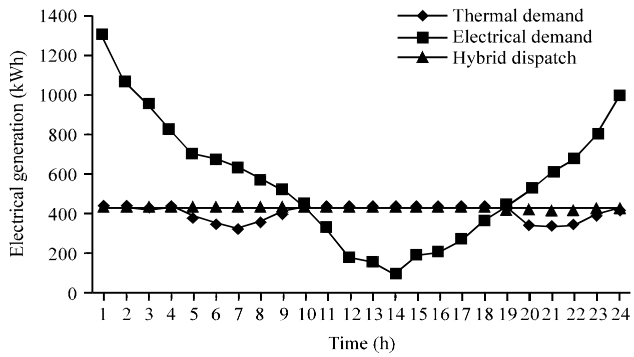

Fig. 5: Thermal output

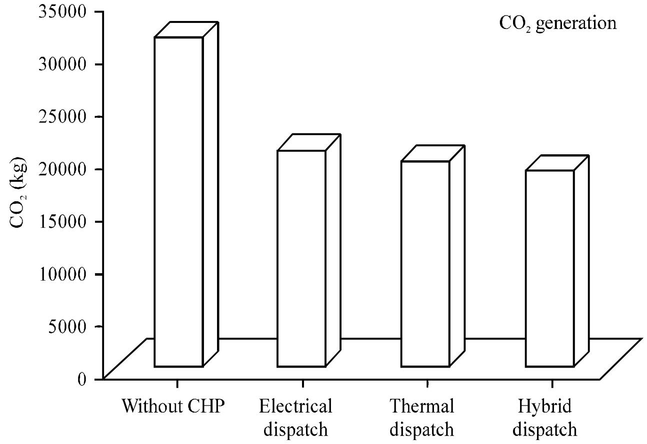

Fig. 6: Amount of CO_2 generation for each strategy in a day

The amount of CO_2 production: As it is observable from Fig. 5, the amount of CO_2 production is different for each strategy. It is important to mention that here it is assumed that for the calculation of CO_2 production the available power plants are gas fired plants. It is obvious that in case of using other power plants, the amount of generated CO_2 would be different. But, what is important is that in case of without CHP the amount of generated CO_2 is greater as shown in Fig. 5.

This result is due to low efficiency of distribution system as well as efficiency of power plants. It is also concluded from Fig. 6 that among different ways of CHP utilization, electrical strategy has the largest amount of CO_2 production because a lot of unusable heat is generated in this situation as illustrated in Fig. 7.

The Hybrid Dispatch has the smallest amount of CO_2 generation among different strategies because as it is observable from Fig. 8, the smallest amount of energy or fuel input is related to this strategy. It is also observed from Fig. 8 that in case of thermal dispatch, the smallest amount of fuel and input energy is used for supplying the electrical and thermal needs.

Overall thermal efficiency: As explained in part IV, overall thermal efficiency index represents the amount of useful energy absorbed in the system. In measurement of this index, there is no difference between thermal energy and electrical energy. Figure 9 shows that in all of the strategies, the use of CHP causes increasing the utilization and the more proper use of fuel. In this

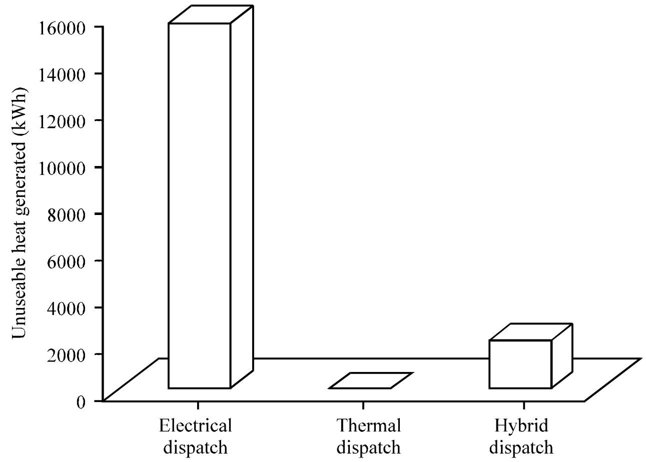

Fig. 7: Unusable generated heat during a 24 h period

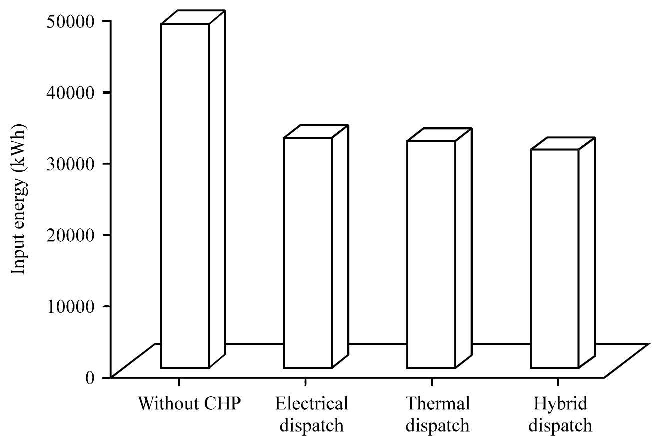

Fig. 8: Energy or fuel input for each strategies

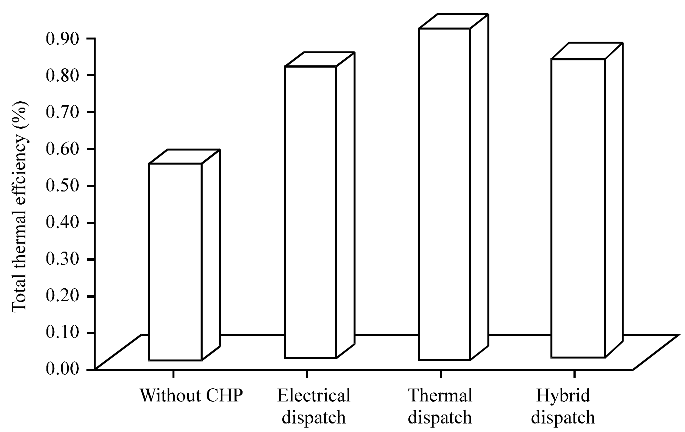

Fig. 9: Percentage of total thermal efficiency for different methods

example, when there is no CHP, the utilization of fuel is around 50% in both electrical and thermal cases. But, by using the cogeneration, this efficiency has a considerable increase. As it was

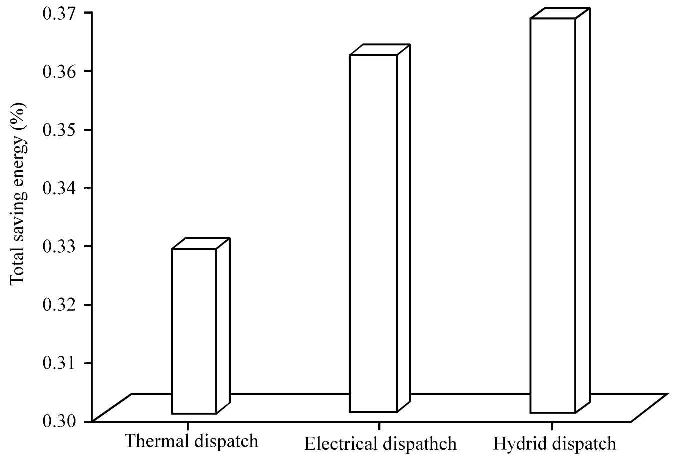

Fig. 10: Total energy saving for each individual operation of CHP

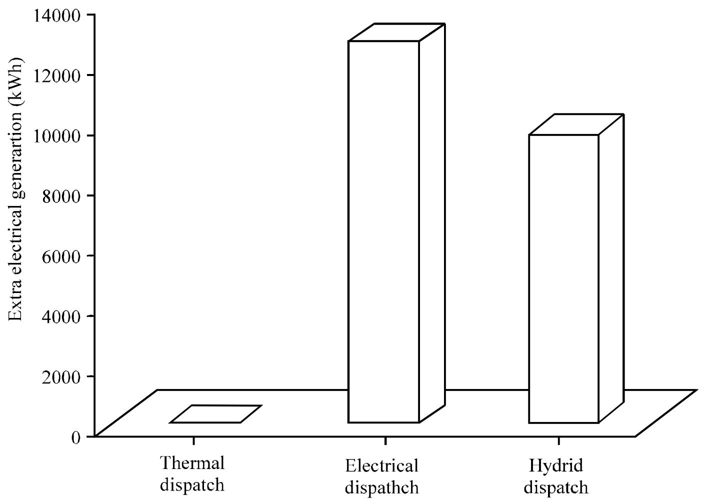

Fig. 11: Excessive generated electricity in case of using each strategy

expected, it has the highest efficiency because in this strategy, the heat is generated appropriately as it can be seen in Fig. 3. In other words, according to definition of this strategy, no excessive heat is produced and all of the heat that could be absorbed is used and extra generated electrical energy is sold to the market in this case. Therefore, the fuel is greatly utilized.

Overall energy saving: This quantity shows how to use the input fuel for generating the electrical energy. It is clear that the more the electrical efficiency of CHP be, the grater the overall energy saving would be.

As it is observed in Fig. 10, from the viewpoint of CHP system operator, in case of hybrid dispatch the most utilization from fuel is achieved for generating the electrical energy because the fuel used in this strategy is less than other strategies and a large amount of electrical energy is generated more than the amount of unit consumption (Fig. 11) and its wasted amount of thermal energy is also small (Fig. 7).

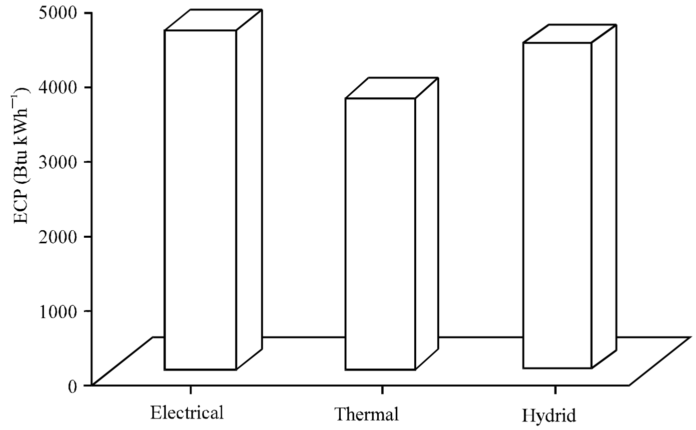

Fig. 12: Energy-chargeable-to power

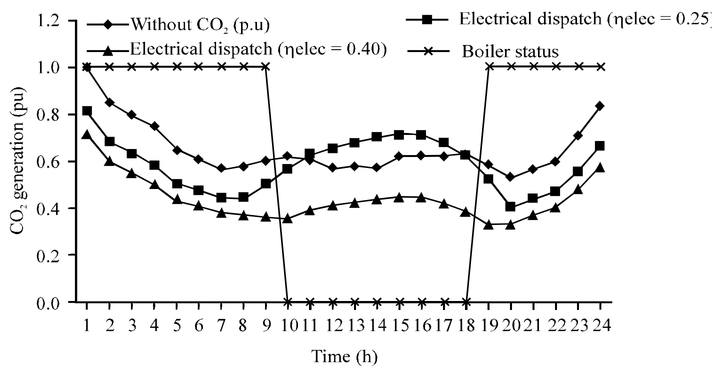

Fig. 13: CO_2 production when electrical efficiency is 25 and 40%

Actually, the generation of CHP based on optimization methodology presented in hybrid strategy is such that the most efficiency of fuel and input energy is occurred and the least cost is imposed on the operator. As illustrated in Fig. 8, in case of thermal dispatch the most excessive electrical energy is generated and given to the network.

Energy-chargeable-to power (ECP): This quantity has been shown for three strategies in Fig. 12. As it can be seen, this index has the least amount in case of thermal dispatch. This result indicates that the generated electrical energy per kWh for electrical dispatch, thermal dispatch and hybrid dispatch has been calculated 4639, 3683 and 4784 Btu kWh^{-1}, respectively. Note that to generate one kWh by a gas fired plant 10000 Btu kWh^{-1} is normally needed.

Actually to calculate this index, it is assumed that the thermal generation is the first priority and beside this, a part of input energy has been absorbed due to generating electrical energy. As it is illustrated in Fig. 12, the minimum ECP has been calculated for thermal dispatch.

The impact of CHP electrical efficiency: CHP electrical efficiency is one of the most important factors in choosing the kind of CHP. In regions where a little thermal need is required, if the electrical strategy is used, it is necessary to consider that if CHP electrical efficiency is less than the efficiency of power distribution network the CO_2 generation may increase. Figure 13 represents that at hours when there is no need to boiler, i.e., when the heat generated by CHP is enough, if CHP efficiency is less than the efficiency of power network, the CO_2 production increases.

It is obvious that in case of thermal dispatch, the amount of electrical efficiency has no effect on generated CO_2 because factors that determine the amount of input fuel in this case are the thermal efficiency and the thermal demand but for low electrical efficiency can influence on other indexes such as ECP, thermal efficiency and overall saving.

CONCLUSION

Considering the increase in fuel price and available concerns about environmental pollutants, currently the usage of CHP is greatly growing. The utilization of this system is done by different strategies. In this study, the efficiency of three different strategies namely; electrical dispatch, thermal dispatch and hybrid dispatch have been considered. Each of these strategies has its own advantage and drawbacks and the operator of CHP system has to choose the appropriate strategy. The profiles and results of this research show that the hybrid dispatch strategy has the best performance and is the best choice in most cases. Therefore, the operation of cogeneration in hybrid dispatch strategy is suitable for both from the view point of the operator and the society.

NOMENCLATURE

Acronyms:

CHCP	=	Combined heat, cooling and power
CHP	=	Combined heat and power
ICE	=	Internal combustion engine
MT	=	Micro turbine
ECP	=	Energy chargeable to power
GHG	=	Greenhouse gas
CCP	=	Cost chargeable to power
SP	=	Separate production
DG	=	Distributed generation
GTCC	=	Gas turbine combined cycle
IGCC	=	Integrated gasification combined cycle
GTCHP	=	Gas turbine combined heat and power
COP	=	Coefficient of performance

List of symbols: Subscripts used for symbols represent the types of energy (p = power, t = thermal and c = cooling):

p	=	Electricity demand
t	=	Thermal demand
c	=	Cooling demand
c_1	=	Network electricity cost
c_2	=	Price of electricity sold by DG
c_p	=	Cost of electricity generated by CHP
η_e	=	Electrical efficiency of conventional power plant
η_{ab}	=	Efficiency of absorption chiller

η_p = Electrical efficiency of CHP unit
η_h = Thermal efficiency of CHP unit
η_n = Electrical efficiency of network
η_t = Thermal efficiency of boiler
h = Heat produced by the CHP unit
p_0 = CHP rated power
P_{chp} = CHP output power
c_b = Cost of boiler
e_{sc} = Electricity required for site chiller start up
P_{ex} = Excessive power generated by CHP unit
p_{sh} = Shortage of power related to demand
å = A very small value
c_{sc} = Cost of site chiller
p_{c1} = Price of electricity purchased from network
p_{c2} = Price of electricity sold to network (profit)
total = Total cost for CHCP unit after subtracting profit

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