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REDUCTION IN CO_2 EMISSION AND FUEL EXERGY SAVING THROUGH COGENERATION FOR SUSTAINABLE DEVELOPMENT

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ABSTRACT

The depletion of non-renewable energy sources and its high cost, along with global warming related problems, have led engineers to re-assess more efficient and eco-friendly energy utilization. The objective of this paper is to determine the magnitude of fuel exergy saving and CO_2 emission reduction from combined heat and power plants in comparison to separate heating and power generation plants. The energy and exergy efficiencies have been defined for different types of energy plants. The efficiency of the cogeneration unit and the CO_2 emissions of the power plant are the two major factors that determine the amount of reduction in CO_2 emission. The expression for fuel exergy saving through cogeneration is also developed in terms of the second-law efficiency of cogeneration plants and the second-law efficiencies of separate heating and power generation plants. The exergy saving is determined for various kinds of cogeneration arrangements. From the results of the study, it is observed that maximum exergy will be saved in internal combustion based cogeneration plants and minimum exergy will be saved through extraction-condensing steam turbine based cogeneration. Results also show a similar trend for CO_2 emission reductions. It is observed that with the increase in efficiency of the power plant and cogeneration, the CO_2 emission decreases. A reduction in CO_2 emission ranges of 20%–25% is possible depending on the conditions. The proposed methodology may be quite useful in the selection and comparison of combined energy production systems in terms of CO_2 reduction, within the framework of the Kyoto Protocol on climate changes.

Keywords: cogeneration, CO_2 emission reductions, fuel-exergy savings, sustainable development.

1 INTRODUCTION

Concerns about potentially dangerous changes in the climate as a result of rising levels of greenhouse gases in the atmosphere are leading to restrictions on emissions of carbon dioxide (CO_2), the principal anthropogenic greenhouse gas. It is the main cause of global warming and if not checked, may lead to irreversible and serious consequences for the climate, including rainfall, sea-level rise and associated effects. The exact magnitude of the change in climate and its likely impacts are still very uncertain. Nevertheless, this is generally recognized as being a serious threat to the earth. As a result, many governments have accepted the Kyoto Protocol and are trying to decrease emissions of greenhouse gases.

Table 1 gives values of specific CO_2 emissions from different types of power plants, along with different primary energy sources and fuel types.

The thirst for extra power for rapidly increasing industrial, conventional and residential consumption has made the reduction of CO_2 emission a more challenging job. The rate of combustion of hydrocarbons since the last many decades has been increasing. If not today, the level of CO_2 in the atmosphere will soon reach the threshold dangerous level if the present trend of combustion of fuels containing carbon continues. Figure 1 shows the increase in concentration of CO_2 in the atmosphere since the start of fossil fuel use. Under the Kyoto Protocol on climate changes, most of the developed countries (except USA) agreed to reduce their emissions of six greenhouse gases to 5.2% below the 1990 levels over the period 2008–2012. However, this alone cannot control the continuing increase in the atmospheric concentration of CO_2, therefore greater reductions in emissions will be required in the future.

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Table 1: Specific CO_2 emissions (kg/kW h) from power plants of various types [1].

Type of power plant	Fuel/energy	CO_2 emissions (kg/kW h)
Steam power plant with FGCU	Lignite	1.04–1.16
Steam power plant with FGCU	Hard coal	0.83
IGCC power plant	Lignite coal	0.91
Gas plant with ICG	Pit coal	0.79
Thermal power plant	Fuel oil (heavy)	0.76
Gas turbine power plant	Natural Gas	0.58
Thermal power plant	Natural Gas	0.45
Gas power plant	Natural gas	0.38
Pressurized water reactor nuclear power plant	Natural Uranium	0.025
Solar thermal power plant	Solar energy	0.1–0.15
Photovoltaic plant	Solar energy	0.1–0.2
Wind power plant	Solar energy	0.02
Hydro-electric power plant	Hydro power	0.004

FGCU, fuel gas conditioning unit; ICG, integrated coal gasification; IGCC, integrated gasification combined cycle.

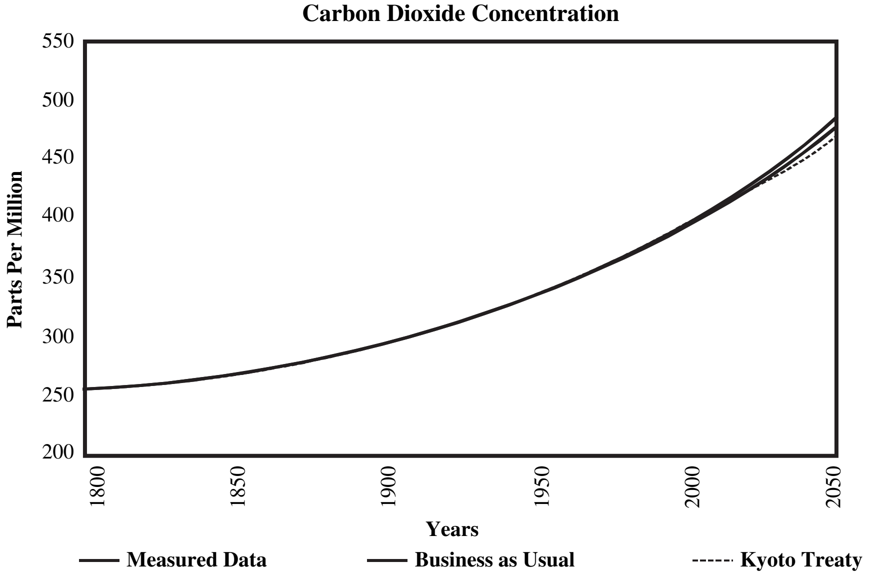

Figure 1: Increase in concentration of CO_2 emissions on yearly basis [2].

There are two ways of reversing the general unfavorable trend of increasing CO_2 concentration in the atmosphere: the first is the containment and capture of CO_2 from the fossil fuel fired power plants and the second is the intensification of energy production leading to significant reduction in CO_2 emissions. The first option of capturing CO_2 is non-sustainable, as it will reduce the overall generating efficiency and output of the plant because of the extra energy used by the capturing and separation equipments as well as the energy used for compression of the gas for transmission [3].

Combined heat and power (CHP) production that yields plant efficiencies much higher than conventional power plants seems to be attractive with respect to energy production intensification. However, it is important to know how effective these systems are with respect to global warming. The idea of using CHP is simple and arises from the fact that in a conventional power station a large amount of heat is rejected (the amount of electricity produced and heat rejected are generally equal). Moreover, heat and electricity consumption are also of the same order of magnitude, on average each is about one-third of the total energy consumed. From these two observations, one could easily argue that the energy production should be organized to satisfy both needs, i.e. electricity and heat from the same energy production system.

Requirement of CHP or cogeneration may be met in several ways, from steam and gas turbines to fuel cells and Stirling engines. Maidment and Tozer [4] have reviewed a number of combined energy operating production plants and analyzed different schemes of combined energy production.

Thermodynamic analysis can be a perfect tool for identification of techniques to improve the efficiency of fuel use and to determine the best configuration for the cogeneration plant. Horlock [5] has defined the criteria for thermodynamic analysis of CHP plants and performed a comparative study based on these criteria for different configurations of CHP plants. Athansovici *et al.* [6] have presented a unified comparison method for the performance calculation of CHP plants and a comparison between separate and combined production of energy has been made using the proposed method. Rice [7] applied the first law of thermodynamics on cogeneration systems to develop a unique graphic solution showing the interrelationship of the many relevant parameters involved. The thermodynamic analysis based on the first law of thermodynamics is the most commonly used technique. However, it is limited only to the conversion of energy and cannot show how or where thermodynamic losses (irreversibilities) in a system or a process occur. Unlike the first-law analysis, the second-law analysis determines the magnitude of irreversible processes in a system and thereby provides an indicator to the direction in which engineers should concentrate their efforts to improve the performance of thermodynamic systems.

Tuma *et al.* [8] have defined the equations for the calculation of the first-law (energy) efficiency and second-law (exergy) efficiency of a cogeneration system. A comparison between the energy and exergy efficiencies was performed. Meunier [9] carried out the thermodynamic analysis of CHP systems and reported that cogeneration plants are more advantageous than separate energy generation plants, and that a CHP system is much more eco-friendly in terms of first-law efficiencies. Khaliq and Kaushik [10, 11] performed the combined first- and second-law analysis of cogeneration plants and combustion gas turbine cogeneration systems with reheat. They also reported that the inclusion of reheat provides significant improvement in the electrical power output process, heat production, fuel-utilization (energy) efficiency and second-law (exergy) efficiency of cogeneration systems. It was also observed that the combined cycle efficiency and its power output increased sharply up to two reheat stages and more slowly thereafter.

Cogeneration units yield first-law efficiency or energy efficiency much higher than conventional power plants and look attractive for energy production intensification. However, it is important to know the effectiveness of this system for the control of global warming. Cogeneration may become thermodynamically favorable if the same energy production system is organized in such a way as to satisfy the needs of electricity and heat.

None of the previous investigations related with the combined first- and second-law analysis of cogeneration systems included the concerned for CO_2 emission reduction. In this study, a thermodynamic methodology based on first- and second-law analysis has been developed to determine the fuel exergy savings and CO_2 emission reduction from CHP plants.

2 THERMODYNAMIC PERFORMANCE PARAMETERS

The relevant thermodynamic parameters required for evaluating the performance of cogeneration and separate energy generation might be considered as follows:

Fuel utilization efficiency or first-law efficiency of a cogeneration system may be defined as the ratio of all the energy in the useful products to the energy of fuel input. By definition:

$$\eta_{\mathrm{I,cog}} = \frac{\left(\dot{W}_{\mathrm{el,cog}} + \dot{E}_{\mathrm{P,cog}}\right)}{\dot{E}_{\mathrm{in,cog}}}, \tag{1}$$

where $\dot{W}_{\mathrm{el,cog}}$ is the power produced from a cogeneration plant, $\dot{E}_{\mathrm{P,cog}}$ is the useful or process heat energy rate from the cogeneration plant at a temperature T_{P} higher than T_0, the ambient temperature and $\dot{E}_{\mathrm{in,cog}}$ is the energy rate of fuel supplied to the cogeneration plant.

Another parameter commonly used to assess the thermodynamic performance of a cogeneration system is the electric power to process heat ratio, which is defined as

$$\sigma_{\mathrm{cog}} = \frac{\dot{W}_{\mathrm{el,cog}}}{\dot{E}_{\mathrm{P,cog}}}. \tag{2}$$

For both, fuel-utilization efficiency and power to heat ratio, power and process heat are treated as equal. This reflects the first law of thermodynamics, which is concerned with quantity and not energy quality.

Since electric power is more valuable than process heat, because it does not carry any entropy and hence the quality of energy associated with the electric power is higher than process heat (i.e. exergy is always destroyed in any real process). The amount of exergy in useful products to the amount of exergy supplied with the fuel is a more accurate measure of the thermodynamic performance of a

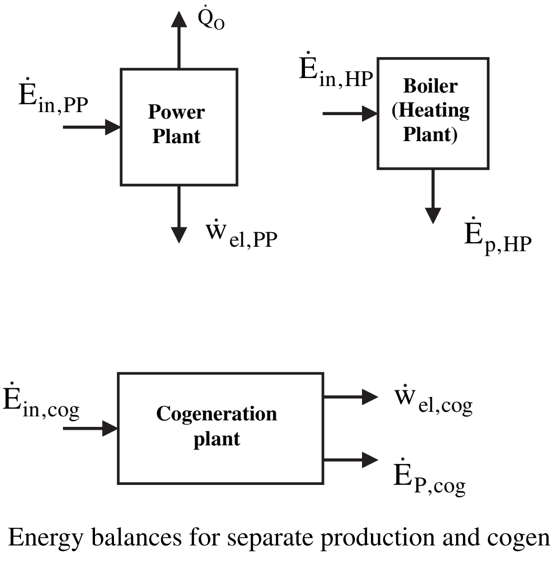

Figure 2: Energy balances for separate production and cogeneration.

system, which is defined as:

$$\eta_{\mathrm{ex,cog}} = \frac{\left(\dot{W}_{\mathrm{el,cog}} + \dot{B}_{\mathrm{P,cog}}\right)}{\dot{B}_{\mathrm{in,cog}}}, \tag{3}$$

where $\dot{W}_{\mathrm{el}}$ is the electric power output, $\dot{B}_{\mathrm{P}}$ is all the exergy content of process heat produced, and $\dot{B}_{\mathrm{in}}$ is the exergy content of fuel input used for cogeneration.

$$\dot{B}_{\mathrm{P,cog}} = \dot{m}_s\left[\left(h_{\mathrm{g}} - h_{\mathrm{c}}\right) - T_{\mathrm{o}}\left(s_{\mathrm{g}} - s_{\mathrm{c}}\right)\right],$$

where h_{g} and h_{c} are specific enthalpies and S_{g} and S_{c} are specific entropies of gaseous and condensate phases.

$$\dot{B}_{\mathrm{in,cog}} = \dot{E}_{\mathrm{in,cog}}\beta,$$

where β ranges from 1.04 to 1.11.

$\dot{E}_{\mathrm{in,HP}}, \dot{E}_{\mathrm{in,PP}}$ and $\dot{E}_{\mathrm{in,cog}}$ may be taken as the product of mass flow rate of fuel and its heating value.

If electric power and useful heat are produced separately in a standard boiler and standard power plant, then the first-law efficiency of steam generator or boiler is defined as the ratio of process heat produced to the amount of energy supplied to the heating plant. It may be given as

$$\eta_{\mathrm{I,HP}} = \frac{\dot{E}_{\mathrm{P,HP}}}{\dot{E}_{\mathrm{in,HP}}}. \tag{4}$$

The first-law efficiency of the power plant is given by

$$\eta_{\mathrm{I,PP}} = \frac{\dot{W}_{\mathrm{el,PP}}}{\dot{E}_{\mathrm{in,PP}}}. \tag{5}$$

The relation for electric power to process heat ratio for the separate energy generation may not have the same value as in cogeneration and is given by

$$\sigma_{\mathrm{sep}} = \frac{\dot{W}_{\mathrm{el,PP}}}{\dot{E}_{\mathrm{P,HP}}}. \tag{6}$$

The second-law efficiency (exergy) of power plant and heating plant may be obtained as

$$\eta_{\mathrm{ex,HP}} = \frac{\dot{B}_{\mathrm{P,HP}}}{\dot{B}_{\mathrm{in,HP}}}, \tag{7}$$

$$\eta_{\mathrm{ex,PP}} = \frac{\dot{W}_{\mathrm{el,PP}}}{\dot{B}_{\mathrm{in,PP}}}, \tag{8}$$

where $\dot{B}_{\mathrm{P,HP}}, \dot{B}_{\mathrm{in,HP}}$ and $\dot{B}_{\mathrm{in,PP}}$ are the exergy associated with process heat, and heat input or energy input to the plant for separate generation of two streams of energy, respectively, and $\dot{W}_{\mathrm{el,PP}}$ is the electric power output of the power plant.

The total exergy destruction and exergy loss rate in the cogeneration plant is smaller than the sum of exergy destruction and exergy loss rates in the two separate plants: power plant for electricity generation and heating plant for the production of process heat.

The fuel exergy savings attainable in the cogeneration plant can be calculated by means of the exergy efficiencies $\eta_{\mathrm{ex,PP}}$ for power plant, $\eta_{\mathrm{ex,HP}}$for heating plant and $\eta_{\mathrm{ex,cog}}$ for cogeneration plant and may be reported as [1]

$$\left(\dot{B}_{\mathrm{f,cog}}\right)_{\mathrm{saving}} = \frac{\dot{W}_{\mathrm{el,PP}}}{\eta_{\mathrm{ex,PP}}} + \frac{B_{\mathrm{P,HP}}}{\eta_{\mathrm{ex,HP}}} - \frac{\dot{W}_{\mathrm{el,PP}} + \dot{B}_{\mathrm{P,cog}}}{\eta_{\mathrm{ex,cog}}}. \tag{9}$$

3 CRITERIA FOR ECO-FRIENDLY CHP PRODUCTION

Cogeneration units always yield higher global efficiencies than power stations. The CHP unit produces electric power and process heat with the efficiencies defined in eqns (1) and (3).

The environmental impact with respect to CO_2 emission is given by

$$I_{\mathrm{cog}} = \dot{E}_{\mathrm{in,cog}}\pi_{\mathrm{f}}, \tag{10}$$

where I_{cog} is the CO_2 emission from the cogeneration unit corresponding to E_{in} and π_{f} is the CO_2 emission per kWh of fuel. If electric power and process heat were produced by conventional means (separately) $\dot{W}_{\mathrm{el,PP}}$ from the power plant and $\dot{E}_{\mathrm{P,HP}}$ from the heating plant with a boiler efficiency η_{b}, the CO_2 emission would be

$$I_{\mathrm{conv}} = \dot{W}_{\mathrm{el,PP}}\pi_{\mathrm{el}} + \frac{\dot{E}_{\mathrm{P,HP}}}{\eta_{\mathrm{b}}}\pi_{\mathrm{f}}, \tag{11}$$

where I_{conv} is the CO_2 emission from the conventional means to get $\dot{W}_{\mathrm{el,PP}}$ and $\dot{E}_{\mathrm{P,HP}}$ and π_{el} is the CO_2 emission per k W h of electricity.

The ratio between CO_2 emissions from the conventional and cogeneration plant is given by

$$R = \frac{I_{\mathrm{conv}}}{I_{\mathrm{cog}}} = \frac{\dot{W}_{\mathrm{el,PP}}\pi_{\mathrm{el}} + (\dot{E}_{\mathrm{P,HP}}/\eta_{\mathrm{b}})\pi_{\mathrm{f}}}{\dot{E}_{\mathrm{in,cog}}\pi_{\mathrm{f}}} = \eta_{\mathrm{I,PP}}\frac{\pi_{\mathrm{el}}}{\pi_{\mathrm{f}}} + \frac{\left(\eta_{\mathrm{I,cog}} - \eta_{\mathrm{I,PP}}\right)}{\eta_{\mathrm{b}}}. \tag{12}$$

The CO_2 emission saving ($\in$) may be obtained as

$$\in = \frac{I_{\mathrm{conv}} - I_{\mathrm{cog}}}{I_{\mathrm{conv}}} = 1 - R^{-1}. \tag{13}$$

The condition for cogeneration to be eco-friendly is $\in > 0$ or $R > 1$ which yields:

$$R = \eta_{\mathrm{I,PP}}\frac{\pi_{\mathrm{el}}}{\pi_{\mathrm{f}}} + \frac{\left(\eta_{\mathrm{I,cog}} - \eta_{\mathrm{I,pp}}\right)}{\eta_{\mathrm{b}}} > 1 \tag{14}$$

$$\Rightarrow \frac{\pi_{\mathrm{el}}}{\pi_{\mathrm{f}}} > \frac{1}{\eta_{\mathrm{I,PP}}} - \frac{\left(\eta_{\mathrm{I,cog}} - \eta_{\mathrm{I,pp}}\right)}{\eta_{\mathrm{b}}\eta_{\mathrm{I,PP}}}.$$

In terms of the second law or exergy efficiency, it may be obtained as

$$\Rightarrow \frac{\pi_{\mathrm{el}}}{\pi_{\mathrm{f}}} > \frac{\dot{E}_{\mathrm{in,PP}}}{\eta_{\mathrm{ex,PP}}\dot{B}_{\mathrm{in,PP}}} - \frac{1}{\eta_{\mathrm{b}}}\left[\frac{\left(\eta_{\mathrm{ex,cog}}\dot{B}_{\mathrm{in,cog}} - \dot{B}_{\mathrm{P,cog}} + \dot{E}_{\mathrm{P,cog}}\right)\dot{E}_{\mathrm{in,PP}}}{\dot{E}_{\mathrm{in,cog}}\eta_{\mathrm{ex,PP}}\dot{B}_{\mathrm{in,PP}}} - 1\right]. \tag{15}$$

4 RESULTS AND DISCUSSION

For the numerical appreciation of this concept, the following data are considered: mass flow rate of steam = 50 kg/s, mass flow rate of fuel burnt = 6 kg/s, condensate temperature = 100°C, and process steam pressure = 10 bar.

Steam is supplied to the steam turbine at $P_s = 100$ bar and $T_s = 500°C$. The condensation occurs at $P_c = 0.05$ bar. The pump work is neglected. The isentropic efficiencies of compressor, gas turbine and steam turbine are each taken as 0.85.

The first-law and second-law efficiencies of various types of fossil fuel fired cogeneration plants and separate energy generation plants are calculated and the magnitude of fuel exergy saving and CO_2 emission reduction are determined using the methodology as discussed previously.

In this section, five cases of different types of cogeneration plants based on internal combustion engine (ICE), combined cycle, gas turbine, back pressure steam turbine and extraction-condensing steam turbine are considered for the assessment of CO_2 reduction and exergy gain.

Table 2 and Figs 3 and 4 show the results for $\eta_b = 0.9$ and $\pi_{el}/\pi_f = 2.0$. The CO_2 emission reduction and fuel exergy saving is shown for various types of cogeneration arrangements with different fuels and for different cogeneration efficiencies. It can be inferred that the CO_2 emission reduction and fuel exergy saving is maximum for ICE-based cogeneration and is minimum for extraction-condensing steam turbine based cogeneration. This is because the ICE-based cogeneration plants are capable of converting up to 90% primary input energy of fuel (as the chemical energy in fuel is all exergy) into electric power and useful heat, which results in higher exergy efficiency of the cogeneration system, and hence the utilization of ICE-based cogeneration plants leads to more fuel exergy savings and lesser CO_2 emissions. On the other hand, in the extraction-condensing steam turbine based cogeneration, because of the lower mass flow rate of steam in the power turbine, lesser amount of electric power will be produced. Steam is extracted at lower pressure from the turbine, which generates the useful heat at a lower temperature, and hence lower exergy will be associated with the useful heat, reducing the exergy efficiency of such cogeneration arrangements significantly.

The extraction-condensing steam turbine based cogeneration is least favorable for the purpose of fuel exergy saving and CO_2 emission reduction.

The CO_2 emission saving due to cogeneration is shown in Figs 5–8 for four values of π_{el}/π_f and three values of η_{cog} as a function of $\eta_{I,PP}$. From eqn (14) as well as from Figs 5–8, it is observed that there exists a minimum value of π_{el}/π_f below which cogeneration is not environment friendly. Taking $\eta_b = 0.9$, $\eta_{cog} = 0.7$ and $\eta_{I,PP} = 0.3$, in eqn (15) leads to $(\pi_{el}/\pi_f) > 1.85$. In fact, the ratio π_{el}/π_f is a figure which is related to CO_2 emission due to electricity production. A high π_{el}/π_f value means an electricity production based on fossil fuel and low technology. If all electricity in a country is produced by fossil fuel power stations whose efficiency is 0.33, then we have π_{el}/π_f as 3, and if the efficiency is equal to 0.5, we get π_{el}/π_f as 2. In a country like India where more than 70% of electricity is being produced from fossil fuel fired plants [10], π_{el} is large. The eqn (15) explains why cogeneration is not competitive when nuclear or hydro-electricity is predominant. It is only competitive with fossil fuel auxiliary power stations. Results plotted in Figs 5–8 show that cogeneration is highly effective when the ratio π_{el}/π_f is high. That corresponds not only to countries in which the power stations have low efficiency but also to countries where auxiliary power stations are used during peak hours. CO_2 emission reduction ranging from 25% to 45% is possible using well-suited cogeneration plants. This means that the substitution of power stations by efficient cogeneration plants can significantly contribute to CO_2 emission reduction. This cogeneration is important in countries where the electricity generation is associated with high CO_2 emission levels.

Table 2: Fuel exergy savings and CO_2 emission reductions from various cogeneration arrangements.

Type of cogeneration plant	Type of fuel used	Heating value (kJ/kg)	Heating plant efficiency $\eta_{\mathrm{I,HP}}$	Electrical power plant efficiency $\eta_{\mathrm{I,PP}}$	Fuel utilization or first-law efficiency of cogeneration $\eta_{\mathrm{I,cog}}$	Heating or second-law exergy efficiency $\eta_{\mathrm{ex,HP}}$	Power plant exergy efficiency $\eta_{\mathrm{ex,PP}}$	Cogeneration exergy efficiency $\eta_{\mathrm{ex,cog}}$	Fuel exergy saving B_{f}	Ratio $R = I_{\mathrm{sep}}/I_{\mathrm{cog}}$	$\pi_{\mathrm{el}}/\pi_{\mathrm{f}} = 2$ CO_2 emission saving $E = 1 - R^{-1}$
ICE-based cogeneration plant	Fuel oil EL	42,700	0.54	0.34	0.88	0.29	0.31	0.64	0.721	1.28	0.218
Combined cycle based cogeneration with back pressure system	Natural gas	37,500	0.42	0.40	0.82	0.21	0.36	0.55	0.621	1.266	0.210
Gas turbine based cogeneration plant with waste heat recuperator	Natural gas	37,500	0.55	0.30	0.85	0.187	0.27	0.44	0.179	1.211	0.174
Back pressure cogeneration plant	Lignite coal	25,955	0.60	0.25	0.85	0.20	0.227	0.40	0.061	1.166	0.142
Extraction-condensing plant based cogeneration	Lignite coal	25,955	0.44	0.38	0.82	0.166	0.34	0.38	0.058	1.037	0.036

EL, extra light.

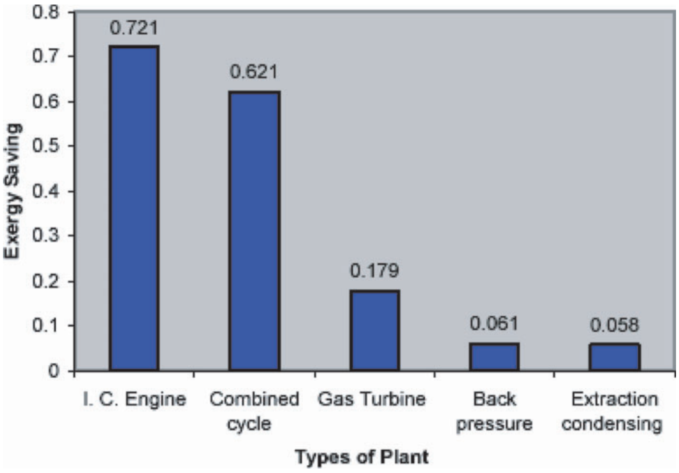

Figure 3: Energy saving for different types of cogeneration arrangements.

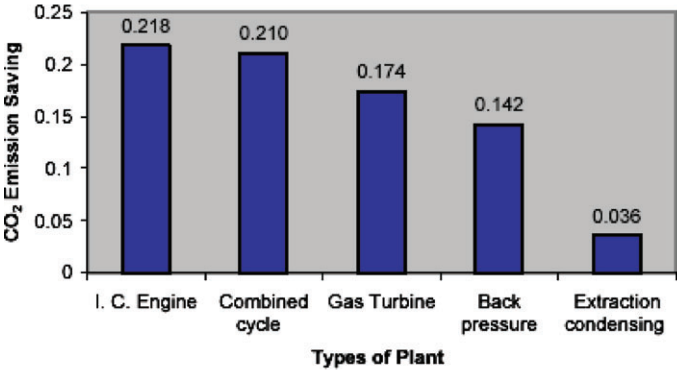

Figure 4: CO_2 emission saving for different types of cogeneration arrangements.

5 CONCLUSION

In the 21st century, changes in climate are anticipated to have potentially serious impacts on all aspects of the natural environment. It is very likely that the CO_2 concentration and hence the overall global temperature will increase in the future. However, the magnitude of impact can be reduced if appropriate policies including energy strategy are developed. Engineers and scientists can play an important role in eco-friendly power generation. Thermodynamic analysis has been carried out for the cogeneration system and found to be eco-friendly with substantial fuel exergy saving in terms of energy and exergy efficiencies. CO_2 emission reduction and exergy savings are determined through various fossil fuel fired cogeneration plants. Reduction in CO_2 emission ranging from 25% to 45% is possible using well-suited cogeneration plants. Among the various arrangements of cogeneration, the maximum fuel exergy saving and the maximum CO_2 emission reduction was found for ICE-based cogeneration and the minimum of these two parameters was found for extraction-condensing steam turbine based cogeneration. The CO_2 emission reduction was found to be a function of cogeneration efficiency and power plant efficiency. It was found that as the efficiency of the power plant and the cogeneration increases, CO_2 emission decreases.

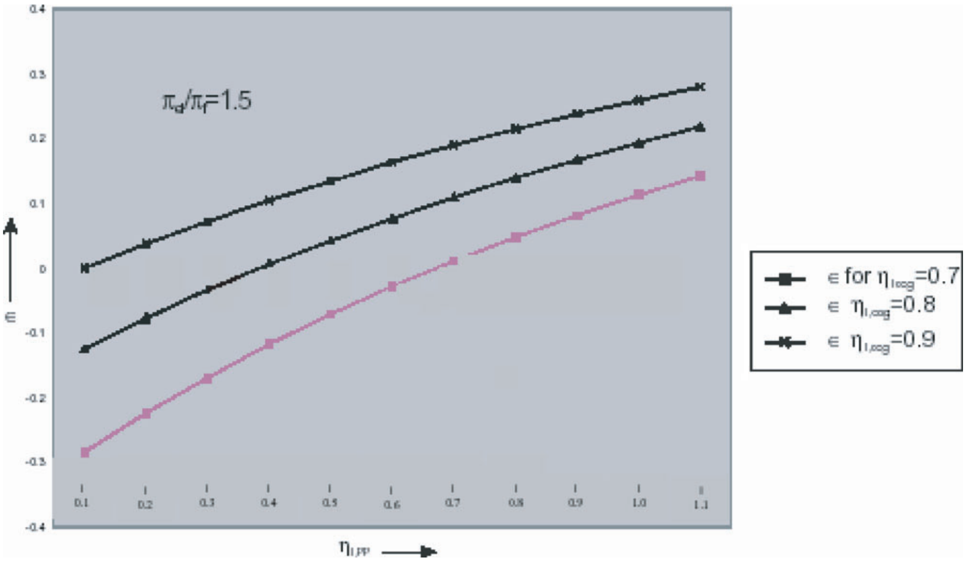

Figure 5: CO_2 emission saving versus $\eta_{I,PP}$ for the CHP system for $\pi_{el}/\pi_f = 1.5$.

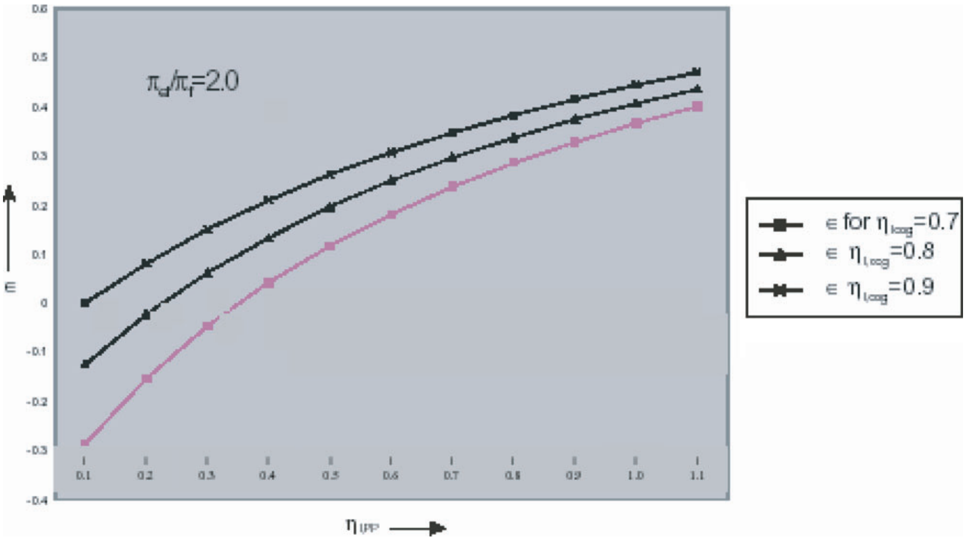

Figure 6: CO_2 emission saving versus $\eta_{I,PP}$ for the CHP system for $\pi_{el}/\pi_f = 2.0$.

CHP is not environment friendly if electricity is produced from renewable or nuclear energy. Priority should be given to renewable and nuclear electricity. Cogeneration must be used only as a substitute for fossil fuel power stations.

The technology proposed in this work is easily implementable. In the 21st century, efforts are being made to generate electric power through hydro, solar, wind, ocean and geothermal renewable energies.

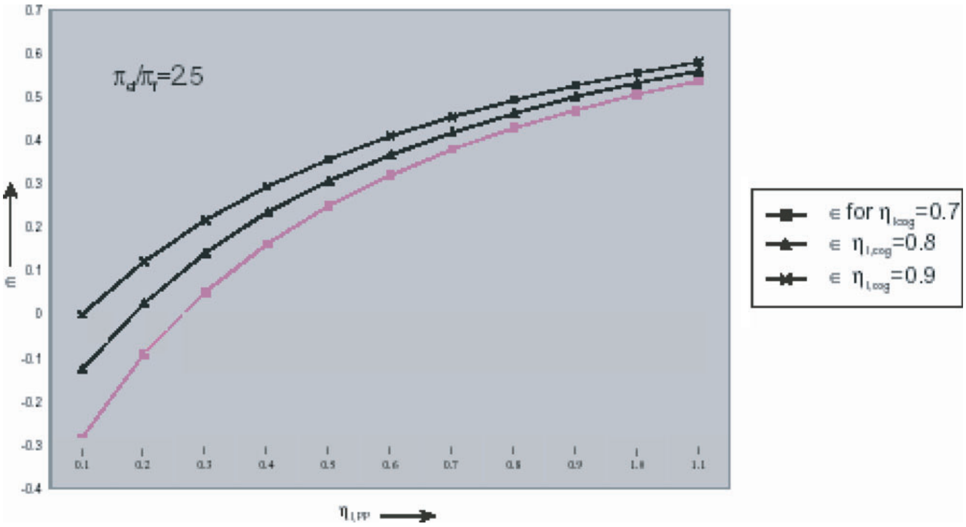

Figure 7: CO_2 emission saving versus $\eta_{I,PP}$ for the CHP system for $\pi_{el}/\pi_f = 2.5$.

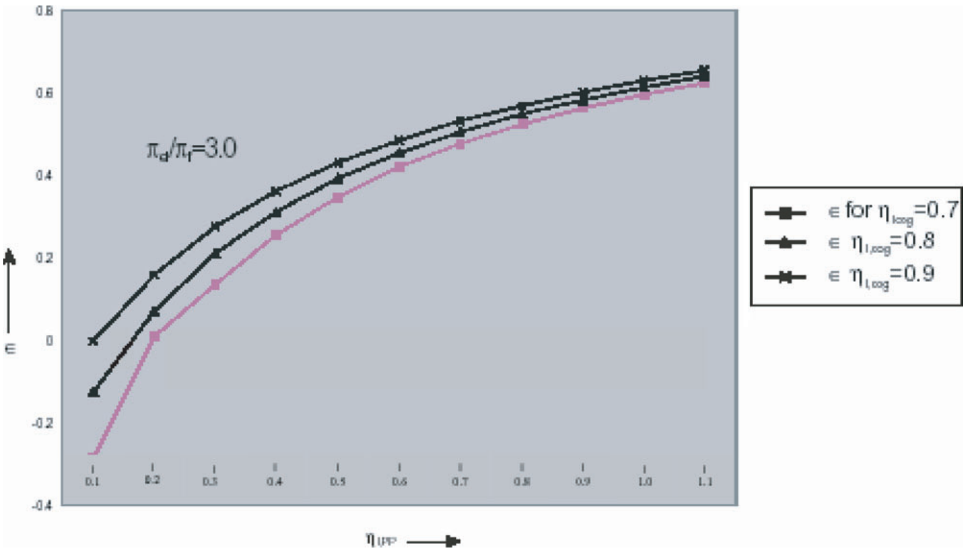

Figure 8: CO_2 emission saving versus $\eta_{I,PP}$ for the CHP system for $\pi_{el}/\pi_f = 3.0$.

For these renewable energies, cogeneration is not competitive and also the need to save fuel exergy is not felt because it is free of cost. Still, the major power requirements of the world are met through conventional fuels or fossil fuels, which are not only costly but also emit CO_2 in large amounts. Hence, there is a need for an international agreement to reduce CO_2 emission for sustainable development.

NOMENCLATURE

E	energy (kJ)
B	exergy (kJ)
H	specific enthalpy (kJ)
M	mass (kg)
P	pressure (bar)
S	specific entropy
T	temperature (K)
W	work (kJ)
R	ratio between the conventional and cogeneration CO_2 emissions
Q	heat transfer (kJ)
I	environmental impact

Greek symbols

η	efficiency
σ	power to heat ratio
β	exergy to energy ratio
π	CO_2 emission per kWh
$\in$	CO_2 emission reduction factor

Subscripts

b	boiler
cog	cogeneration
el	electrical
HP	heating plant
PP	Power plant
S	steam
P	process
in	inlet
c	condensate
g	gaseous phase
sep	separate
ex	exergy
I	first law
f	fuel

REFERENCES

[1] Khartchenko, N.V., *Green Power: The Eco-friendly Energy Engineering – Fundamentals and Design*, Tech Books International: New Delhi, 2004.

[2] Laurence, O.W., *An End to Global Warming*, Pergamon Press: Oxford, 2002.

[3] Freund, P., Making deep reductions in CO_2 emissions from coal-fired power plant using capture and storage of CO_2. *Proc. Instn. Mech. Engrs. Part A: Journal of Power and Energy*, **217**, pp. 1–7, 2003.

[4] Maidment, G.G. & Tozer, R.M., Combined cooling heat and power in super markets. *Applied Thermal Engineering*, **22**, pp. 653–665, 2002.

[5] Horlock, J.H., *Cogeneration – Combined Heat and Power (CHP): Thermodynamics and Economics*, Pergamon Press: Oxford, UK, 1987.

[6] Alhanasovici, V., Lecorre, O., Brecq, G. & Tozerout, M., Thermoeconomic analysis method for cogeneration plants. *Proceedings of ECOs' 2000*, Netherlands, pp. 157–164, 2000.

[7] Rice, I.G., Thermodynamic evaluation of gas turbine cogeneration cycles: Part I – Heat balance method analysis. *Journal of Engineering for Gas Turbines and Power*, **109**, pp. 1–7, 1987.

[8] Tuma, M., Oman, J. & Sekavenik, M., Efficiency of combined gas-steam process. *Energy Conversion and Management*, **40**, pp. 1163–1175, 1999.

[9] Meunier, F., Co- and tri-generation contributions to climate change control. *Applied Thermal Engineering*, **22**, pp. 703–718, 2002.

[10] Khaliq, A. & Kaushik, S.C., Second-law based thermodynamic analysis of Brayton/Rankine combined power cycle with reheat. *Applied Energy*, **78(2)**, pp. 179–197, 2004.

[11] Khaliq, A. & Kaushik, S.C., Thermodynamic performance evaluation of combustion gas turbine cogeneration system with reheat. *Applied Thermal Engineering*, **24**, pp. 1785–1795, 2004.