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Feasibility analysis of different cogeneration systems for a paper mill to improve its energy efficiency

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ABSTRACT

Cogeneration is considered as one of the promising energy efficient techniques for producing electricity and useful thermal energy from a single fuel source. This paper describes a feasibility study of the implementation of different cogeneration options to a paper mill to evaluate their energy saving potentials and economic benefits. The investigated systems in this paper are gas turbine, steam turbine and combined cycle cogeneration options evaluated and compared based on energy utilisation factor and Annualised Life Cycle Cost (ALCC) analysis. The results of energy analysis show that all Combined Heat and Power (CHP) systems satisfy the thermal energy needs of the mill while the combined cycle cogeneration option generates the highest amount of electric energy equal to 10.91 MW. The gas turbine cogeneration system is shown as the most advantageous system from overall energy point of view with the highest energy utilisation factor of 78% meeting the heat and electric requirements of the mill and exporting 21,329 MWh of additional electricity to the grid. Economic feasibility results also show that an overall saving of 5.12 million US$ can be achieved by implementing the gas turbine cogeneration system to the mill making it as the best cogeneration option with the least overall ALCC of 1.34 million US$ and the maximum percentage of CO_2 emission reduction (68%) when compared with the other options.

Introduction

In a changing global energy landscape, where energy demand is forecasted to be doubled by the year 2050 and tripled by the end of the century [1], energy conservation and management are becoming increasingly important. Practical energy management methods and the development of energy systems with minimal costs and high efficiencies are vital to balance our future energy demands with the limited world's energy resources. Cogeneration system also known as combined heat and power (CHP) is an efficient energy utilisation method which can provide the sequential generation of two different forms of useful energy, (i.e. electrical and thermal energy) from a single fuel input. The system can utilise both fossil fuels and renewable fuels such as biomass as the source of energy. As one of the most important and widely available renewable energy resource in agricultural countries rice husk as biomass, which is the major by-product generated from the rice milling industry, can be used as an alternative energy

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source to substitute fossil fuel for providing industrial heat and power and reducing greenhouse gas emissions. Bhattacharyya has analysed the viability of a scaled-up electricity supply system with reduced cost using rice husk [2]. It is shown that the use of rice husk as a source of power can support the application of this waste to a viable energy generation technology.

Combustion, pyrolysis and gasification are three main thermochemical conversion methods for the utilisation of biomass for heat and power generation in commercial application. Generally combustion of biomass is carried out in excess oxygen, gasification in controlled oxygen and pyrolysis is operated in inert atmosphere in the absence of oxygen. Several studies are conducted on gasification [3] and [4], pyrolysis [5] and [6] and combustion [7] to produce energy in the form of syngas, liquid fuel, heat and electricity respectively using rice husk as the fuel.

Gasification through partial oxidation at high temperatures converts biomass into a gaseous mixture of syngas consisting of hydrogen (H_2), carbon monoxide (CO), methane (CH_4) and carbon dioxide (CO_2) [8]. The process is considered more efficient than the combustion process for producing power and heat [9] and [10]. The energy content of the syngas produced in a gasification process depends on many factors, such as the type of biomass used, gasifier configuration and operating conditions, gasifying agent (i.e. air, steam, oxygen, CO_2 or their mixture), the gas residence time and the biomass feeding rate [11]. For instance a lower heating value (LHV) of 4–6 MJ/m^3 for syngas is obtained when air is used as the gasifying agent, a medium heating value of 12–18 MJ/m^3 when steam is used and a much higher heating value of about 40 MJ/m^3 is obtained when hydrogen is used as gasifying agent [12]. Furthermore the type of gasifier utilised also affects the LHV of produced syngas significantly. The heating value of syngas obtained by the gasification of rice husk in an industrial-scale circulated fluidized bed gasifier is reported as 4.6–6.3 MJ/m^3 while a heating value in the range of 3.8–4.6 MJ/m^3 is reported when a downdraft fixed bed gasifier is used [13].

Although the syngas can be used alone or co-fired with natural gas to generate heat and power [14], many studies have shown that a combination of fossil fuel and biomass could be more beneficial since gas turbines fuelled by only biomass normally cannot achieve a turbine inlet temperature (TIT) required to maintain a high efficiency [15] and [16]. Other drawbacks of the cogeneration systems when using biomass as the single source of energy are limitations in terms of fuel flexibility, availability and the system reliability. Although biomass derived syngas has been used in combustion engines since 1881 [17] many researchers have discussed various technical risks and benefits associated with employing biomass in CHP technologies [17–20]. Among different types of biomass CHP technologies, Biomass Integrated Gasification Combined Cycle (BIGCC) technology identified as an efficient, safe, clean and cost-effective method for power generation [21] and [22], has been successfully used in recent years in which the most of technological problems associated with the application of biomass derived syngas are addressed and resolved.

The BIGCC technology consists of a high-pressure gasifier, hot-gas-cleaning system, a prime mover (i.e. gas turbine, gas engine, steam turbine or other internal combustion engine) and a generator. The BIGCC plants can significantly increase the efficiency of the electricity generation from biomass in comparison with conventional biomass combustion plants [23]. This technology is considered as one of advanced power generation technologies with expected electric efficiencies of more than 40% for large-scale plants with electricity generation in the range of 30–50 MW [24].

There are many examples of the use of BIGCC technologies worldwide including biomass gasification plants developed in the USA, Finland, Brazil, etc. [15,25–27]. Fahlen and Ahlgren [28] evaluated the integration of a biomass gasification plant into a district-heating system where a combined cycle fuelled with natural gas and syngas was used. The results show that integration of a biomass gasification plant into a district-heating system reduces the net emissions of CO_2 and is economically profitable. This solution (BIGCC –CHP) was later considered by Difs et al. [29] to operate a plant with a power rating of 2 MW (electrical) and heat flux amounts to 4 MW (thermal) in Austria.

Kimming et al. [30] performed a comparative life cycle assessment to supply the power and heat to a rural village using biomass produced on farm-land in a small-scale combined heat and power plant. The result of their analysis showed that the CHP plant option would considerably reduce greenhouse gas emissions compared to the scenario based on fossil fuel. Another study by Burritt et al. [31] analysed carbonisation and cogeneration as two processing alternatives to reduce environmental and social impacts related to the conventional way of rice husk disposal and to improve the overall performance of the rice mill in Philippines. A comparative technical and economical assessment of biomass gasification for a biomass based combined heat and power generation in the Cuban context studied by Perez et al. [32] also shows an overall efficiency of 33.3%, the internal rate of return (IRR) of 12% resulting in a payback period of 5.3 years for the project lifespan of 15 years. Soltani et al. [33] and [34] studied a thermodynamic performance of biomass based externally fired gas turbine for power generation. In a recent study by Pode et al. [35] rice husk biomass has been used as a sustainable fuel for rural electrification in Myanmar. It has been shown that the rice husk biomass power system is not only the sustainable and affordable option to rural electrification but can be considered as a financially viable business model to provide the grid quality power to rural population.

The combination results of these studies show that in all cases, the utilisation of rice husk as biomass guarantees the power demands of the process with surplus electricity generation, low level of pollution, low ash content and low sulphur concentration in addition to the use of a renewable and cheap source of energy for heat and electricity generations.

As the world's fourth largest industrial energy user that consumes around 6% of total world industrial energy, the pulp and paper manufacturing industry involves highly energy intensive processes [36]. The continuous needs for heat and electricity in this sector make it an ideal process for overall energy saving through the implementation of a suitable cogeneration option. Therefore this study is aimed to assess the implementation of different CHP options to Pakistan's pulp and paper sector that has a share of 7% in total industrial energy consumption in the country [37] by evaluating its feasibility for a paper mill. Fig. 1 shows the share of different fuels to the overall thermal energy used in Pakistan's paper sector. As seen rice husk is used as the main source of energy along with other fossil fuels in Pakistan's paper sector where its use is advantageous due to its significant availability, low price and also from sustainable energy balance and environmental points of view.

Despite few feasibility studies on the application of cogeneration systems in Pakistan industrial sectors [39], the practical implementation of CHP options in Pakistan industries is not yet ensued. Given the fast growth of the Pakistan's pulp and paper sector and its significant contribution to the country's total industrial energy consumption, the implementation of cogeneration to this sector is of interest and a better understanding of its potentials for energy savings appears to be worthy. Therefore in this study primary analysis of the implementation of different CHP options to a medium scale paper mill is performed and the existing energy situation of the mill and its potential energy savings when different cogeneration systems implemented are assessed and compared in details on the basis of overall energy efficiency and economic analysis.

In this study three possible cogeneration configurations (i.e. gas turbine, steam turbine, combined cycle) are applied to a paper mill located in the urban area of Lahore, Pakistan. The potential energy saving, electricity production, process heat recovery, electrical efficiency and energy utilisation factor of the mill for each cogeneration option are calculated and compared to find the best cogeneration option for the mill from both energetic and economic points of view. The effect of fuel ratio on the operating cost and total CO_2 emission of the mill are also assessed.

It is believed that the use of rice husk as a renewable fuel and analysing its energetic and economic benefits from sustainable energy balance and economical points of view presented and discussed in this paper will have a definite impact on research into the feasibility analysis and implementation of high efficient CHP systems using wastes such as rice husk as alternative source of energy for energy saving, cost optimization and CO_2 emission reduction in other industrial sectors. Such an investigation is therefore timely not only because of the current interest in high performance CHP options, but also from the scientific point of view.

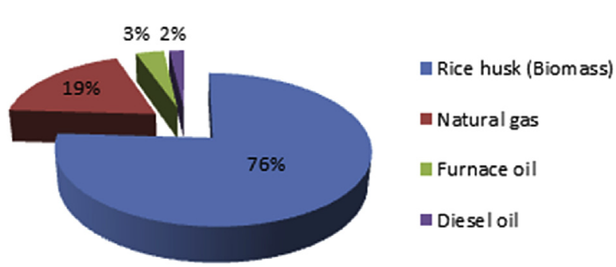

Fig. 1 – Share of fossil & renewable fuels consumed in Pakistan's paper sector [38].

Case study

The mill analysed in this study has three paper production lines that use Neutral Sulphite Semi-Chemical (NSSC) process for production of un-bleached board with annual production capacity of 44,417 tonnes. The electrical and thermal energy requirements of the mill based on the data obtained from Cleaner Production Institute (CPI) Pakistan are shown in Fig. 2. The average annual electricity and thermal energy demands of this plant are calculated as 4307 kW and 17,380 kW respectively where the average annual electricity demand of the mill is considered as the projected electrical energy generation when implementing different CHP options to the mill later.

At the current situation the mill uses rice husk as the fuel to provide 55% and natural gas to provide 45% of its annual process thermal energy requirements sequentially in a cycle. The required electricity for the mill is supplied by the grid and the mill operates with a high electricity load factor of 0.9 and a heat to power ratio of 4:1 continuously indicating higher demands for thermal energy compared to its electricity demands.

To improve the energy efficiency of the mill, the implementation of different CHP options to the mill is studied and the results of energetic and economic analysis are compared. A detailed description of each cogeneration system; their process flow diagrams; the methodology applied for their implementation and also their energetic and economic analysis are presented as follow.

Methodology

All proposed cogeneration configurations contain five main components including a gasifier, a prime mover (gas or steam turbine); heat exchangers for heat recovery; a gas clean-up section and electric generator. These components are selected based on thermal load matching to meet the mill's thermal energy requirements in the form of saturated steam. In all cases, the plant is designed to operate with rice husk as biomass fuel for 4026 h and then with natural gas for 3294 h in a continuous cycle. With this configuration, the cogeneration plant would generate electric energy in the range of 4–11 MW which is typical of a small to medium scale cogeneration plant. As the plant is installed in an urban development area, the surplus electric energy generated could be exported to the grid and due to the vicinity of the local rice husk resources to the plant economic factors related to the transport of rice husk are not considered in the calculations.

Steam turbine configuration

In the steam turbine cogeneration system shown in Fig. 3, superheated steam is generated through direct combustion of fuel (rice husk or natural gas) in the boiler which then is expanded in a steam turbine to generate electricity. The

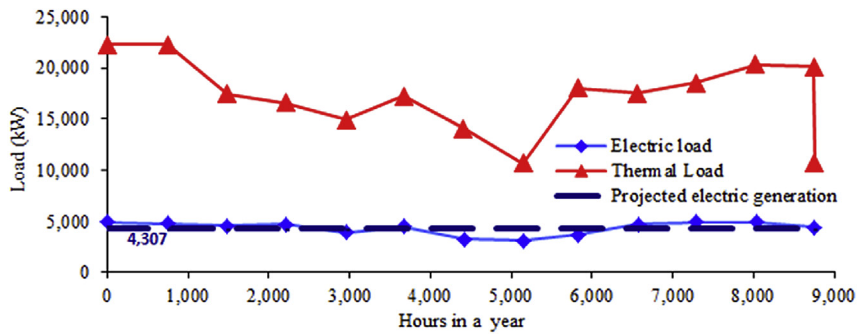

Fig. 2 – Energy demand and projected electrical energy generation of mill [38].

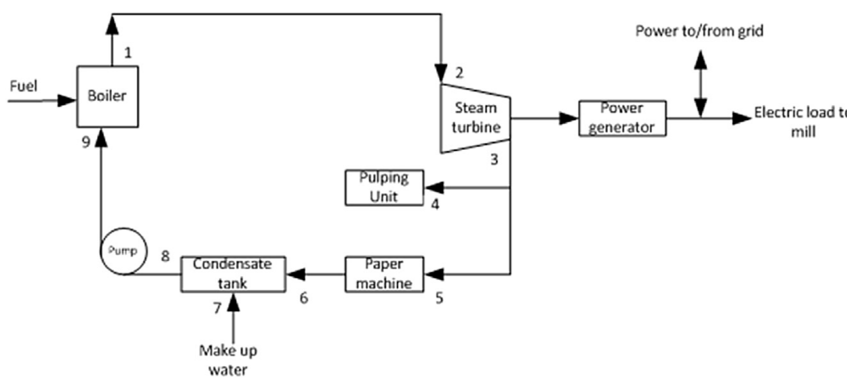

Fig. 3 – Schematic diagram of the proposed steam turbine cogeneration system.

saturated steam leaving the turbine is used to meet the process heat demands of the paper mill. The system enables production of both heat and electricity for the mill. A detailed energy and economic analysis of this configuration is discussed in the results & discussion section.

Gas turbine configuration

In gas turbine cogeneration system when using rice husk as the fuel, the dried biomass is introduced into a gasifier to produce syngas which in turn is sent to a storage tank after gas cleaning process. The gas-cleaning system mainly includes a cyclone separator, a tar cracker, venture tubes, water scrubbers, an electrostatic tar-catcher and a gas storage tank. The gas cleaning process is critical to the operation of this plant. The syngas leaving the storage tank is burnt in the combustion chambers of the gas turbine for electricity generation and the final exhaust gas stream leaving the turbine is utilised for steam generation in a heat recovery steam generator (HRSG) with the aid of supplementary fuel firing to meet the process heat requirements. When natural gas is used as the fuel, it is directly burnt in the combustion chamber and then follows the same processes as explained for the syngas. This cogeneration option operates in a continuous cycle switching between the fuels using rice husk for 4026 h and natural gas for 3294 h alternately to produce process heat and electricity as shown in Fig. 4. Flow arrangement and temperature of different streams in HRSG are indicated in Fig. 5.

Combined cycle configuration

Combined cycle system utilises both gas and steam turbine systems for energy generation where rice husk is converted to syngas in a gasifier and then utilised in the combustion chamber before entering the gas turbine. When natural gas is used, it is directly introduced into the combustion chamber of gas turbine. Similar to the gas turbine configuration the exhaust gas stream from the gas turbine is utilized in HRSG for steam generation with supplementary fuel firing. Steam produced in HRSG of a combined cycle system process is superheated steam that is used in a steam turbine for electricity generation. The saturated steam leaving the steam turbine is then used to fulfil the thermal needs of steam mill as shown in Fig. 6.

Comparison of different cogeneration systems

All abovementioned cogeneration configurations have been analysed and compared from both energetic and economic points of view. To make the different cogeneration options comparable, the steam requirements of the mill in terms of steam temperature, pressure and flow rate (10 bars, 180 °C and 8.63 kg/s) in three different CHP options are considered the

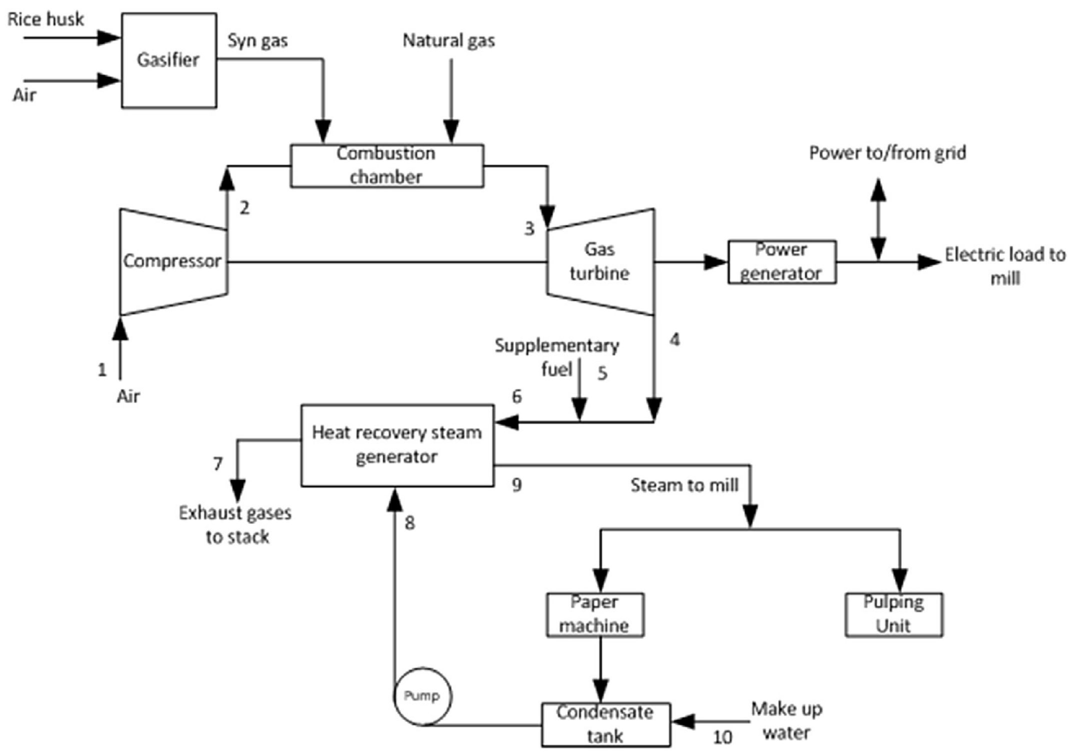

Fig. 4 – Schematic diagram of the proposed gas turbine cogeneration system.

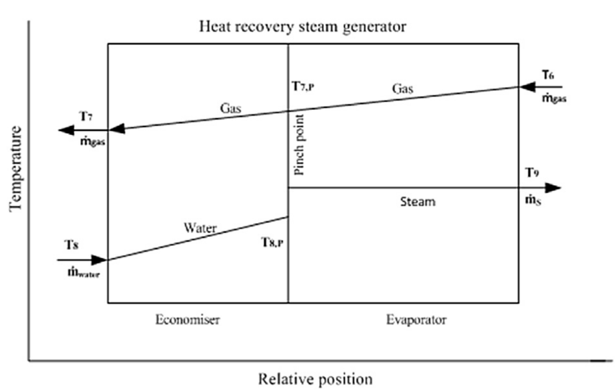

Fig. 5 – Temperature profile and flow arrangement in HRSG.

same. The results of energetic and economic analyses are explained in details as follow.

Energetic analysis of proposed CHP configurations

Many researchers have used energetic analysis to study and compare the performance of different cogeneration systems [17] and [30]. In this study energetic analysis is used as an expedient tool to identify the possible ways of improving the efficiency of fuel use and determine the best configuration for implementing a cogeneration plant to a paper mill. Prior to the energetic analysis of CHP systems, all assumptions made, fixed parameters considered and the equations used to evaluate the energy balance in each proposed CHP configuration are explained. The main assumptions made follow as: ideal gas principles are applied to air and combustion gases, the system operates in steady state and all combustion reactions are complete. The fixed parameters used for the evaluation and comparison of three CHP configurations are given in Table 1.

Steam turbine cogeneration calculations

In order to analyse steam turbine cogeneration system energetically, the Rankine cycle is applied to the steam turbine configuration in which the condenser is changed by chemical process units of paper mill (i.e. pulping and paper machine as shown in Fig. 3). With this arrangement it is assumed that the energy released in the condenser of the Rankine cycle is instead transferred to the mill. The mass flowrate of steam, $\dot{m}_s$, required from the boiler is calculated by the thermal energy, E_{th}, required by the mill in the form of saturated steam divided by the enthalpy difference between steam used in paper machine and pulping unit, h_3, and the condensate returned to the mixing tank, h_6, as shown in Fig. 3. This can be shown by the following expression [40]:

$$\dot{m}_s = \frac{E_{th}}{(h_3 - h_6)} \quad (1)$$

Similarly heat input into the boiler, Q_{bl} can be calculated from Equation (2) where h_1 and h_9 are enthalpies of steam leaving and water entering the boiler respectively and η_b, is the thermal efficiency of the boiler.

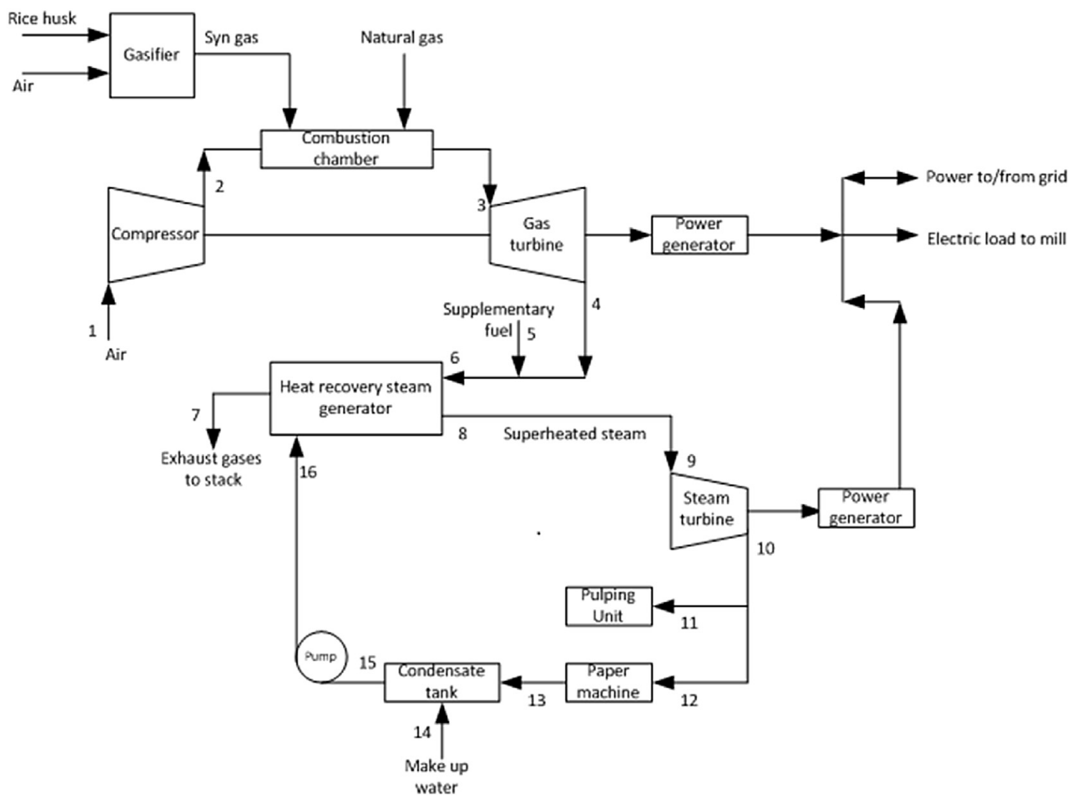

Fig. 6 – Schematic diagram of the proposed combined cycle cogeneration system.

Table 1 – Summary of fixed parameters used for various plant components.

Parameter	Value	Parameter	Value
η_b (Boiler efficiency)	0.80	T_o (K)	288
η_{gen} (Generator efficiency)	0.97	P_o (kPa)	101.32
η_{st} (Steam turbine efficiency)	0.85	$\Delta T_{approach}$ (K)	8.33
η_{gt} (Gas turbine efficiency)	0.85	ΔT_{pinch} (K)	8.33
η_c (Compressor efficiency)	0.82	steam quality, x_{out}	0.95
η_{cc} (Combustion Chamber efficiency)	0.98	$C_{p,gas}$ (kJ/kg K)	1.148
η_p (Pump efficiency)	0.80	$C_{p,air}$ (kJ/kg K)	1.004
LHV of rice husk (kJ/kg)	15,217		
LHV of natural gas (kJ/kg)	46,250		

$$Q_{bl} \equiv \frac{\dot{m}_s(h_1 - h_9)}{\eta_b} \quad (2)$$

The work done by the steam turbine is equal to the amount of power produced by the turbine that depends upon the flow rate of steam into the turbine and the enthalpy difference between the inlet and outlet steam from the steam turbine when the efficiency of the turbine is already accounted into the exhaust enthalpy of turbine as shown in Equation (4):

$$W_{st} = \dot{m}_s(h_2 - h_3)\eta_{gen} \quad (3)$$

η_{gen} is the thermal efficiency of the generator and h_3 is the enthalpy of the outlet steam from the turbine at real conditions which can be calculated by:

$$h_3 = h_2 - (\eta_{st}(h_2 - h_{3s})) \quad (4)$$

Where h_2 is the enthalpy of steam at the turbine inlet, η_{st} is the efficiency of the steam turbine and h_{3s} is enthalpy of steam after isentropic expansion through the turbine.

By equating the amount of steam consumed at pulping unit (PU) at stream 4 with make-up water at point 7, the pump work is calculated by Equation (5) where $\dot{m}_{l,}$ is the mass flow rate of water in steam 8 leaving the condensate tank, v_8 is the specific volume of saturated liquid at the pump inlet, P_8 and P_9 are pressures at the pump inlet and outlet respectively:

$$W_P = \dot{m}_l v_8(P_9 - P_8) \quad (5)$$

The net power for the steam turbine cogeneration system is defined as the difference between the total power generated by the steam turbine, W_{st}, and the power used by the pump, W_P, and is calculated as:

$$W_{net} = (W_{st} - W_p) \quad (6)$$

The thermal energy recovery by the steam turbine system which is equal to the amount of process heat used by the mill, Q, in the form of saturated steam is calculated as follow [41]:

$$Q = \dot{m}_s(h_3 - h_f) \quad (7)$$

Where, h_f is the enthalpy of saturated liquid at turbine outlet.

The mill's process heat, Q, is then used later as the process heat requirement Q in Equation (32) to calculate the energy utilisation factor for steam turbine cogeneration system.

Gas turbine cogeneration calculations

In this section the procedures for the energetic analysis of gas turbine cogeneration system shown in Fig. 4 are presented. It is assumed that the values of pressure ratios (P_4/P_3) and (P_2/P_1) are the same. Both P_1 at the air compressor inlet, and P_7 at the outlet of HRSG are at the ambient pressure P_o. The temperature of inlet gas to the turbine, T_3, is fixed and depends on the maximum temperature at which the highly stressed parts of the turbine can stand. This temperature is critical to the turbine's working life as the metallurgical limit temperature provided by turbine manufacturers. This value of T_3 is fixed at 1400 K according to the reference value for small to medium scale gas turbines given by Knopf FC [42].

The actual work of the compressor is determined by the Brayton cycle based on the ideal gas assumptions for air. The air compressor isentropic exit temperature, T_{2s}, can be obtained by the following expression [42]:

$$T_{2s} = T_1\ (P_2\ /\ P_1)^{(\gamma_{air}-1)/\gamma_{air}} \tag{8}$$

Where (P_2/P_1) is the air compression ratio, γ_{air} is the specific heat ratio of air and T_1 is the inlet air temperature which is equal to the ambient temperature T_o.

The isentropic exit temperature T_{2s} is then corrected to the actual exit temperature T_2 by considering the compressor efficiency η_c according to the following equation [42]:

$$T_2 = T_1 + \frac{1}{\eta_C}(T_{2s} - T_1) \tag{9}$$

The amount of work done by the air compressor can be calculated by Equation (10):

$$W_C = \dot{m}_{air} C_{p_{air}} (T_1 - T_2) \tag{10}$$

Where, $\dot{m}_{air}$ and C_{Pair} are the mass flow rate and the average specific heat capacity of air respectively.

The mass flow rates of the fuel added to, $\dot{m}_{fuel}$, and exhaust gases, $\dot{m}_{gas}$, from the combustion chamber are calculated by applying material and energy balances around the combustion chamber according to the Equations (11) and (12) assuming that both the air and the product gas from the combustion chamber are ideal gases [42].

$$\dot{m}_{gas} = \dot{m}_{fuel} + \dot{m}_{air} \tag{11}$$

$$\begin{aligned}(\dot{m}_{air} + \dot{m}_{fuel}) C_{P_{gas}} (T_3 - T_o) + \dot{m}_{fuel}(LHV_{fuel})(1 - \eta_{CC}) \\ = \dot{m}_{fuel}(LHV_{fuel}) + \dot{m}_{air} C_{P_{air}} (T_2 - T_o)\end{aligned} \tag{12}$$

Where LHV is the lower heating value of the fuel and η_{cc} is the efficiency of combustion chamber and $\dot{m}_{fuel}$ is defined by the Equation (13) as follow:

$$\dot{m}_{fuel} = \frac{\dot{m}_{air} C_{p_{gas}} (T_3 - T_o) - \dot{m}_{air} C_{p_{air}} (T_2 - T_o)}{LHV \eta_{CC} - C_{p_{gas}} (T_3 - T_o)} \tag{13}$$

$\dot{m}_{air}$ is the mass flow rate of the air calculated based on 228% excess air used. Then the rate of heat added to the combustion chamber can be calculated by the Equation (14) given below:

$$Q_{CC} = \dot{m}_{fuel}(LHV_{fuel}) \tag{14}$$

and the turbine isentropic exit temperature $T_{4S,}$ is calculated by Equation (15) as follow:

$$T_{4s} = \frac{T_3}{P_4/P_3\left(1 - f_{pd}\right)^{\left(\gamma_{gas}-1/\gamma_{gas}\right)}} \tag{15}$$

The P_4/P_3 ratio is the pressure ratio based on the inlet and outlet of gas pressures, γ_{gas} is the specific heat ratio of gas and f_{pd} is the frictional pressure drop in the combustion chamber. This temperature is then corrected to the actual exhaust gas temperature of T_4 by considering gas turbine efficiency, η_{gt}, by the following equation:

$$T_4 = T_3 - \eta_{gt}(T_3 - T_{4s}) \tag{16}$$

Power generated by the gas turbine can be calculated by Equation (17):

$$W_{gt} = \dot{m}_{gas} C_{p_{gas}} (T_3 - T_4) \tag{17}$$

And finally the net power for the gas turbine cogeneration system defined as the difference between the total power generated by the gas turbine and the power used by the air compression can be calculated as:

$$W_{net} = (W_{gt} - W_c)\eta_{gen} \tag{18}$$

The amount of steam produced in HRSG is calculated based on the heat integration method used by Ganapathy in which both the pinch temperature difference ΔT_{pinch} and the approach temperature difference $\Delta T_{approach}$ are generally fixed between 8 and 11 K [43]. Smaller the values of ΔT_{pinch} and $\Delta T_{approach}$ will result in a higher value for heat transfer surface area which eventually increases the cost of HRSG.

The values of gas flow rate, $\dot{m}_{gas}$, gas temperature at HRSG inlet, T_4, and feed water temperature, T_8, are known and the temperature of saturated steam from HRSG, T_9, is set at 180 °C as required by the mill steam demand. The amount of steam generated in HRSG and the temperature of exhaust gases from HRSG, T_7, can be determined by material and energy balances around the economizer and evaporator sections of the HRSG as follows:

$$T_{7,P} = T_9 + \Delta T_{pinch} \tag{19}$$

$$T_{8,P} = T_9 - \Delta T_{approach} \tag{20}$$

Where, $T_{7,P}$ is the pinch point temperature in stream 7 defined as the difference between the gas temperature leaving the evaporator and the temperature of saturated steam. Similarly the pinch point temperature in stream 8, $T_{8,P}$, is the difference between the temperature of saturated steam and the temperature of the water entering the evaporator.

The amounts of the heat added to the evaporator, Q_{evap}, and the economiser, Q_{econ}, can be calculated as follow:

$$Q_{evap} = \dot{m}_{gas} C_{p_{gas}} (T_{7,P} - T_6) \tag{21}$$

$$Q_{econ} = \dot{m}_{water}(h_{8,P} - h_8) \tag{22}$$

Where, $\dot{m}_{water}$, is the mass flow rate of water equal to $\dot{m}_s$ and T_6 is the temperature of exhaust gases from the turbine entering HRSG after mixing with the supplementary fuel. In the case of no supplementary fuel firing both temperatures T_6 and T_4 are the same. $h_{8,p}$ and h_8 are the enthalpies of water at temperatures $T_{8,P}$ and T_8 respectively. The mass flow rate of saturated steam from HRSG can be calculated by:

$$\dot{m}_s = \frac{Q_{evap}}{(h_9 - h_{8,P})} \tag{23}$$

The value h_9 used in the equation is the enthalpy of steam leaving HRSG at T_9. The exhaust gas after losing energy to the water in HRSG leaves the stack with the temperature of T_7 calculated by:

$$T_7 = T_{7,P} - \left(\frac{Q_{econ}}{\dot{m}_{gas} C_{p_{gas}}}\right) \tag{24}$$

Since the flow rate of steam produced in HRSG is not satisfying the required steam flow rate demand of the mill; hence a supplementary firing of fuel is required. The flow rate of this supplementary fuel, $\dot{m}_{fuel,SF}$, can be calculated by the knowledge of LHV for the fuel using the following equation:

$$\dot{m}_{fuel,SF} = \frac{\dot{m}_{gas} C_{p_{gas}} (T_{6,SF} - T_4)}{LHV - C_{p_{gas}} (T_{6,SF} - T_o)} \tag{25}$$

Both energy and material balances around HRSG must be corrected for the supplementary fuel added. The new values of the flow rate of steam, $\dot{m}_{s,SF}$, flow rate of gas, $\dot{m}_{gas,SF}$, heat added to the evaporator, $Q_{evap,SF}$, economiser, $Q_{econ,SF}$, stack temperature, $T_{7,SF}$, and the efficiency of HRSG, η_{HRSG}, are recalculated and corrected by the following expressions:

$$\dot{m}_{s,SF} = \frac{\dot{m}_{gas,SF} C_{p_{gas}} (T_{6,SF} - T_{7,SF})}{(h_9 - h_8)} \tag{26}$$

$$T_{7,SF} = \frac{\dot{m}_{s,SF}(h_9 - h_{8,P}) - \left(\dot{m}_{gas,SF} C_{p_{gas}} T_{6,SF}\right)}{\left(\dot{m}_{gas,SF} C_{p_{gas}}\right)} \tag{27}$$

$$Q_{evap,SF} = \dot{m}_{gas,SF} C_{p_{gas}} (T_{6,SF} - T_{7,SF}) \tag{28}$$

$$Q_{econ,SF} = \dot{m}_{water,SF}(h_{8,P} - h_8) \tag{29}$$

$$Q_{net,HRSG} = Q_{evap} - Q_{econ} \tag{30}$$

$$\eta_{HRSG} = \frac{Q_{evap,SF} + Q_{econ,SF}}{(\dot{m}_{gas,SF} h_{6,SF} + \dot{m}_{fuel,SF} LHV_{fuel})} \tag{31}$$

Combined cycle cogeneration calculations

The combined cycle cogeneration system consists of a combination of both steam and gas turbine systems where the superheated steam introduced to the steam turbine in this case is provided by HRSG. The same methods and equations used in the calculations for steam turbine and gas turbine configurations are applied to each part here.

Cycle efficiency of CHP options

The cycle efficiency of all proposed cogeneration configurations are expressed in terms of energy utilization factor, ε_u, and is defined as the ratio of net electric power output P plus the energy recovered in the form of steam for the process heat requirements, Q, divided by the total energy input of fuel [44]:

$$\varepsilon_u = \frac{P + Q}{m_{fuel} CV_{fuel}} \tag{32}$$

Economic analysis of proposed CHP configurations

Profitable deployment of CHP solutions strongly depends on the simultaneous demand of thermal and electric energy in a wide time span over the year [45]. Cogeneration options are typically applied to industries with annual operating hours above 4500 [46] and [47]. Since the actual annual operating hours of the mill considered in this case study (≈7,320 h) is more than the recommended industrial annual operating hours, implementation of the proposed cogeneration options to the mill is expected to allow for surplus electricity generation and additional thermal energy savings.

The ALCC analysis is widely used to determine the most cost-effective option among different competing alternatives. The economic assessment and comparison of the cogeneration options applied in this work are performed based on Annualised Life Cycle Cost (ALCC) analysis calculated by the following equation [48]:

$$ALCC = I_e R + C_o - (FS_{CHP} + C_{PP}) \tag{33}$$

Where I_e is the initial investment cost of the equipment, R is the capital recovery factor, C_O is the annual operating cost of the equipment, FS_{CHP} is the financial savings from cogeneration by selling the surplus electricity to the grid and C_{pp} is the avoided cost of power purchase. The avoided cost is defined as the energy and capacity costs that the utility would avoid through the generation of power by a cogeneration facility [49]. The average values of the energy and capacity costs set by local electricity supplier in the area of proposed cogeneration system are 0.097(US$/kWh) and 3.6(US$/kW) on a monthly basis respectively [50]. The exchange rate used in this study is 1US$ = 100Pak Rupees [51].

The capital recovery factor R for a cogeneration system can be calculated as:

$$R = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{34}$$

Where i is the interest rate and n is the useful life of the equipment in years [42]. The value of R for all three cogeneration options used in this study are calculated based on Pakistan's government guidelines for biomass cogeneration project with an interest rate of 11.5% and a life cycle of 30 years [39]. The maintenance cost for cogeneration systems with natural gas as the main fuel is taken as 6% of the total equipment cost [52], whereas the value of 10% of the total equipment cost is assumed for the maintenance cost when rice husk is used as the main fuel [53]. This is due to the formation of higher amount of ash fouling and slagging in the boiler in case of steam turbine cogeneration and requirement of syngas cleaning for gas turbine cogeneration systems.

The investment cost of equipment, I_e, at different operating conditions are estimated from the relationships given in

Table 2 – Relationships for the calculation of the investment cost of major equipment's.

Parameter	Equation	
Boiler	$I_{bl} = 740(Q_{bl})^{0.8} \exp\left(\frac{P_1 - 2}{14.29}\right) \exp\left(\frac{T_1 - 350}{446}\right)$	(35)
Pump	$I_P = 3540(W_P)^{0.71}$	(36)
Air compressor	$I_C = \left(\frac{75\dot{m}_{air}}{0.9 - \eta_C}\right)\left(\frac{P_2}{P_1}\right)\ln\left(\frac{P_2}{P_1}\right)$	(37)
Electric generator	$I_{gen} = 60(W_{net})^{0.95}$	(38)
Gas turbine	$I_{gt} = \left(\frac{1536\dot{m}_{gas}}{0.92 - \eta_{gt}}\right)\ln\left(\frac{P_3}{P_4}\right)(1 + \exp(0.036T_3 - 54.4))$	(39)
Steam turbine	$I_{st} = 6000(W_{net})^{0.7}$	(40)
Combustion chamber	$I_{CC} = \left(\frac{48.64\dot{m}_{air}}{0.995 - \frac{P_3}{P_2}}\right)(1 + \exp(0.018T_3 - 26.4))$	(41)
Gasifier	$I_{gasifier} = 1600(\dot{m}_{ricehusk})^{0.67}$	(42)
HRSG	$I_{HRSG} = 3650\left(\left(\frac{Q_{econ}}{LMTD_{econ}}\right)^{0.8} + \left(\frac{Q_{evap}}{LMTD_{evap}}\right)^{0.8}\right) + 11820\dot{m}_s + 658(\dot{m}_{gas})^{1.2}$	(43)

Table 2 where the cost of installation, electrical equipment, control systems, piping are taken into account in the coefficients used in each equation [42,52–54].

The feasibility of a cogeneration system mainly depends on the key economical parameters such as the investment costs, electricity tariffs, fuel costs, exchange rate and interest rate. The price of rice husk and natural gas used as the main fuels are taken as 0.10 and 0.28 (US$/kg) respectively. These are the actual current prices that the mill is paying for its fuels [38]. The price of electricity for paper mill is estimated to be about 0.15 (US$/kWh) based on the average price (peak and non-peak) of electricity for the period of 1st January–31st December 2014 [50]. The price of electricity transferred to grid taken from Pakistan's government guidelines is 50% of the actual cost of electricity [39].

$$CO_2\ emission = \frac{(Amount\ of\ fuel\ used \times CO_2\ emission\ factor\ for\ fuel + Amount\ of\ electricity\ purchased \times CO_2\ emission\ for\ grid\ electricity)}{Amount\ of\ energy\ generated} \quad (44)$$

The annual operating cost of a cogeneration system consists of the fuel, labor, and maintenance costs. The labor cost is calculated by assuming an automated gas turbine plant of 8 MW operating at three shifts per day. With this arrangement, the gas turbine will require 18 full time operators [55]. Assuming the turbine operates 8 h per shift for 306 days per year and a wage rate of US$1.42 per hour [56], the direct labor cost is estimated at US$62,570/year. The same calculations are applied to the steam turbine requiring 8 operators per shift and to the combined cycle requiring 12 operators per shift.

CO_2 emission analysis of proposed CHP configurations

The carbon dioxide emissions and the emission reduction potential per unit total energy generated (thermal and electrical) in kg of CO_2/kWh for different cogeneration options considered for the mill are calculated by expression (44) [57]:

The average CO_2 emission factors used in this study are 0.18407 kg CO_2/kWh for natural gas [57], 0.01731 kg CO_2/kWh for rice husk [38] and 0.47337 kg CO_2/kWh for purchased electricity from grid [58].

Table 3 – Energy balance of proposed cogeneration systems.

Parameters	Units	Existing system	Cogeneration options		
			Gas turbine	Steam turbine	Combined cycle
Energy input	MW	30.11	31.46	28.14	40.04
Electricity production	MW	0	7.22	1.78	10.91
Process heat recovery	MW	17.38	17.38	17.38	17.38
Electrical efficiency	%	0	22.4	6.3	26.7
Energy utilisation factor	%	57.7	78.1	68.1	70.6

Table 4 – Optimal parameters for the proposed cogeneration systems.

Parameter	Cogeneration options		
	Steam turbine	Gas turbine	Combined cycle
$\dot{m}_{air}$ (kg/s)	–	26.79	34.10
T_2 (K)	573	573	573
P_2 (bar)	33	8.106	8.106
$\dot{m}_{fuel}$ (kg/s)	0.61	0.68	0.87
T_3 (K)	453	1400	1400
T_4 (K)	453	925.11	925.11
P_3 (bar)	10	8.065	8.065
h_2 (kJ/kg)	2984.85	–	–
h_{3s} (kJ/kg)	2731.94	–	–
h_f (kJ/kg)	762.68	–	–
h_3 (kJ/kg)	2769.87	–	–
W_c (kW)	–	−7665.59	−9757.24
W_{gt} (kW)	–	14,933.05	19,007.73
W_{st} (kW)	1800.02	–	1814.05
W_p (kW)	24.80	–	24.80
W_{net} (kW)	1775.22	7049.44	10,710
$\dot{m}_S$ (kg/s)	8.63	8.63	8.63
Q_{evap} (kW)	–	17,691.85	17,702.42
Q_{econ} (kW)	–	3009.68	3011.48

Results and discussion

The energy performance of all cogeneration systems is presented in Table 3. The utilisation factor of cogeneration plants is typically in the range of 70–80% [59]. The results of energy utilisation factor for this analysis shows a utilisation factor of 78% for gas turbine, 68% for steam turbine, and 70% for combined cycle indicating that the energy is best used in a gas turbine. The results of energetic analysis for gas turbine and combined cycle show that the entire electric power required for the mill is produced through the cogeneration options, however since the heat of the exhaust gases from the gas turbine are insufficient to produce the steam requirements of the mill, a supplementary fuel firing in heat recovery steam generator is used to compensate for high heat–to-power ratio of 4:1 requirement for the mill as explained in section 2.

The results of energetic analysis for all cogeneration systems operating with optimal parameters given in Table 4 show that the use of rice husk and natural gas with the time ratio explained in the methodology section guarantees the heat requirements of the process in all proposed CHP options and also allows for the generation of surplus electricity when gas turbine or combine cycle are implemented.

The annual fuel consumption, electricity generation and its export to grid, and avoided electricity purchase of all cogeneration options are calculated and summarised in Table 5.

The amount of annual energy savings in the form of natural gas when comparing the existing system with gas turbine and steam turbine cogeneration systems are 2207 and 3063 tonnes of natural gas respectively. This translates to the values of 0.61 and 0.85 million US$ cost savings for the gas and steam turbine cogeneration options respectively. Similarly the amounts of annual energy savings in the form of rice husk when comparing the existing system with gas turbine and steam turbine cogeneration options are 7851 and 11,313 tonnes of rice husk respectively. This translates to the values of 0.62 and 1.01 million US$ cost savings for the gas and steam turbine cogeneration options respectively with possible emission reductions due to the decrease in the use of fuel.

In case of combined cycle cogeneration option, the supplementary firing in HRSG results in more electricity generation with a slight increase in fuel consumption. The results of

Table 5 – Annual fuel consumption and electrical energy production data for existing system and proposed cogeneration options.

Parameters	Units	Existing system		Cogeneration options					
				Gas turbine		Steam turbine		Combined cycle	
Fuel type		Natural gas	Rice husk	Natural gas	Rice husk	Natural gas	Rice husk	Natural gas	Rice husk
Fuel consumption	tonnes	10,277	38,126	8070	30,275	7214	26,813	10,277	38,489
Electricity production	MWh	0	0	23,223	29,632	5863	7166	35,279	44,648
Electricity requirement	MWh	14,187	17,339	14,187	17,339	14,187	17,339	14,187	17,339
Electricity transferred to grid	MWh	0	0	9036	12,293	0	0	21,092	27,309
Electricity bought from grid	MWh	14,187	17,339	0	0	8324	10,173	0	0
Avoided electricity purchases	MWh	0	0	14,187	17,339	5863	7166	14,187	17,339

Table 6 – Summary of the annual operating costs of proposed cogeneration options.

Cost (millions US$)	Gas turbine		Steam turbine		Combined cycle	
	Natural gas	Rice husk	Natural gas	Rice husk	Natural gas	Rice husk
Fuel cost	2.25	3.03	2.02	2.68	2.87	3.85
Electricity purchase cost	0	0	1.32	1.62	0	0
Labor cost	0.028	0.034	0.037	0.046	0.056	0.069
Maintenance cost	0.15	0.31	0.21	0.34	0.25	0.49
Annual operating cost (C_o)	2.43	3.37	3.58	4.69	3.18	4.41

Table 7 – Comparison of ALCC of proposed cogeneration options.

Cost (millions US$)	Gas turbine		Steam turbine		Combined cycle	
	Natural gas	Rice husk	Natural gas	Rice husk	Natural gas	Rice husk
Equipment investment cost	2.46	3.07	3.43	3.43	4.20	4.91
Annual operating cost	2.43	3.37	3.58	4.69	3.18	4.41
Avoided electricity purchases	1.15	2.37	0.40	0.90	0.96	2.18
Financial saving from CHP	0.68	0.92	0	0	1.58	2.05
ALCC	0.90	0.44	3.59	4.20	1.13	0.76
Overall ALCC	1.34		7.79		1.89	

economic analysis of three cogeneration options also show that this is economically beneficial when selling the excess electricity to the grid in a unit cost of 0.075 (US$/kWh). This is four times higher than the unit cost of the fuel used (0.019 (US$/kWh)).

In the case of gas turbine and combined cycle options the supplementary firing would result in increased operation and maintenance costs and additional capital cost for HRSG. Therefore it is always beneficial to maintain the balance between the mills electric/thermal loads and the capital cost of the CHP system as a general rule.

The results of operating cost analysis of the proposed cogeneration systems based on fuel, labor, purchased electricity and maintenance costs are given in Table 6. These results are used for the calculation of annualised life cycle costs (ALCC) given in Table 7.

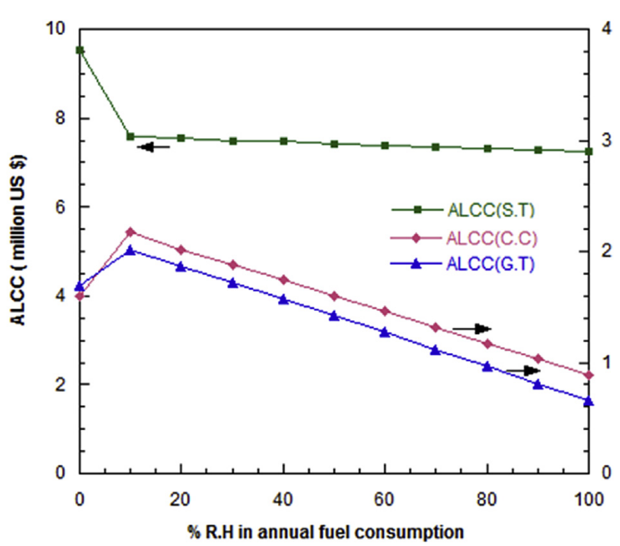

Fig. 7 – Variation of the annualised life cycle cost (ALCC) with the fuel ratio in terms of the percentage of rice husk (% R.H) for different CHP options.

The data given in Table 7 show that from economic analysis point of view the gas turbine cogeneration system has the lowest overall ALCC among different cogeneration options when using natural gas for 4026 h and rice husk for 3294 h in a continuous cycle. This shows that the gas turbine cogeneration system can be considered as the most economical viable option for the paper mill. When comparing with the existing system, the proposed gas turbine cogeneration system will save the avoided electricity purchase cost of 3.52 million US$ in addition to the revenue worth of 1.60 million US$ per year through power export to the grid resulting in an overall saving of 5.12 million US$.

Fig. 7 shows the variation of the mill's economic performance in terms of annualised life cycle cost (ALCC) with the fuel ratio for different CHP options while other factors remain unchanged. As explained before the fuel ratio in this study represents the number of hours of the fuel use in a year. As shown in Fig. 7 the ALCC for steam turbine cogeneration option decreases with increase in the percentage of the rice husk for the entire range of the fuel ratio. It can be seen that the introduction of rice husk with the fuel ratio of 10% (i.e. 732 hrs rice husk use and 6588 h 90% natural gas use) decreases ALCC significantly by 21%. This in mainly due to the lower cost of unit total energy generated by combustion of rice husk compared with the cost of unit total energy generated by the

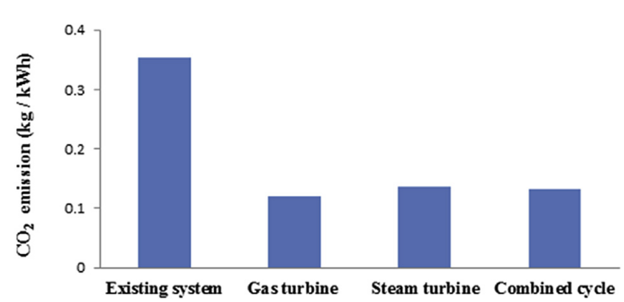

Fig. 8 – CO_2 emission per unit of total energy generated for different CHP options.

combustion of natural gas. For the fuel ratios above 10%, there is still a decrease in the ALCC with increase in amount of rice husk used as fuel; however the effect of fuel ratio on the ALCC becomes trivial probably due to the lower calorific value of rice husk which results in the generation of lower amount of electricity to satisfy the mill's requirements. In this case the reliability on grid to purchase electricity will have negative impact on ALCC.

In the case of gas turbine and combined cycle options there is an increase in ALCC with increase in fuel ratio up to 10%. This can be explained by additional operating costs for gasifier and syngas cleaning system which are not balanced by the lower price of rice husk used as the fuel in this range. As the percent of the rice husk increases above 10% the additional operating costs of gasifier will be balanced and justified by lower cost of the fuel and therefore the ALCC starts to decrease. It is worth to mention that these results are specifically for this particular case study of paper mill where the main aim is to satisfy the thermal requirement of mill and electric generation is not in priority. The results indicated in Fig. 7 show that from economic point of view implementing the gas turbine cogeneration system to the mill would make it as the best cogeneration option with the least overall ALCC when compared with the other options.

Energy generation systems with lower primary energy use or higher energy utilisation factor result in lower CO_2 emissions. The level of CO_2 emissions per unit total energy generated in kg of CO_2/kWh for different cogeneration options considered for the mill is shown in Fig. 8. The CHP technology can be used to reduce the energy usage and hence reduction in CO_2 emission. These results indicate that the implementation of CHP systems is more efficient when compared to the existing system due to their effective use of otherwise wasted thermal energy and concurrent electricity generation. This scenario is in contrast with the conventional system, where no electricity is generated and a significant amount of the energy is lost as wasted heat.

Based on the previous ALCC results and the results of CO_2 emission given in Fig. 8 one can see that the gas turbine CHP option gives the maximum percentage of energy saving and CO_2 emission reduction. The results show that CO_2 emission for gas turbine CHP option is reduced by 68% compared to the existing system. The reasons behind this is mainly due to higher energy utilization factor resulted by the amount of annual energy savings from reduction in natural gas and rice husk consumptions when compared with the existing system and also additional electricity generation. CO_2 emission reduction for steam turbine and combined cycle CHP options compared with the existing system are also calculated as 61% and 63% respectively.

Conclusions

Thermoeconomic viability of different cogeneration options for a typical paper mill is analysed when using rice husk as the biomass with natural gas in alternate cycles as its main energy source. It is found that the mill has a good potential for energy saving through the implementation of cogeneration system when compared with the current system in operation. This has been shown in both technical and economic perspectives based on energy utilisation factor and annualised life cycle cost. The energetic analysis of different options indicated that the gas turbine cogeneration system generates 21,329 MWh of electricity in addition to supplying the required process heat and electricity for the mill which results in an annual saving of 1.6 million US$. Base on the economic analysis, it is also concluded that the gas turbine cogeneration system has the lowest ALCC value considered as the most economical viable option for the paper mill. The results of CO_2 emission analysis also show that gas turbine CHP option gives the maximum percentage of CO_2 emission reduction 68% compared to the existing system. The proposed approach investigated in this study is applicable to a wide range of paper mills in Pakistan to improve their energy efficiency which can help tackling the country's energy crisis as a whole. This method can also be adopted for energy saving and cost optimization in other industrial sectors through the use of biomass as alternative source of energy.

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