The Effect of Using CHP Systems in Energy Utilization and Reduction of Greenhouse Gases in a Pulp and Paper mill in Iran

S. H. Hosseinian, Y. HadjebnAli, P.Orouji

***Abstract*— Pulp and paper industries consume about 6% of the total energy used in the industries worldwide, and are considered some of energy consuming industries. These mills are accounted as one of the attractive choices to implement combined heat and power system. In these industries, the production of steam, at high capacity, by boilers, is necessary for washing, refining and drying stage in the production of pulp and paper.**

In this study, the improvement of combined heat and power system operation was studied in an Iranian pulp and paper mill. In this plant, for the purpose of production of the required steam, two boilers were used. Due to non-conformity of conditions of steam produced by boilers (a pressure of 60 bars and temperature of 445^{o}C) with the steam necessary for the process (a pressure of 12.2 bars and temperature of 200^{o}C), the conversion of produced steam to consumed steam was done by using pressure-reducing valves and this sets the stage of considerable loss of energy. For this reason, the energy recovery potential and production of a portion of electrical energy needed by the plant using the backpressure steam turbine has been studied. In this study, four types of technologies in the utilization of steam turbine have been examined, with each technology being studied in three steam production strategies using thermo-economic analysis.

Results indicate that using above technologies and strategies, under most optimal conditions, reducing in natural gas consumption up to 50% and the equivalent of 41600 tons per year of carbon dioxide greenhouse gas is achieved.

Keywords: Pulp & Paper, Greenhouses Gases, Back Pressure Steam Turbine.CHP Systems.

I. Introduction

Pulp and paper industries consume about 6% of the energy used in the industries throughout the world, and are considered among the energy consuming industries in the world, therefore, having a high potential for reduction in energy consumption [1] . One of these potentials is the improvement in energy management using combined heat and power systems (CHP).

The generation of heat and electrical power within a single facility, as opposed to separate facilities, often results in efficiency improvements in the range of 10–40% [2]. CHP system, in most paper and pulp mills in the world, is based on power and recovery boilers for generation of high pressure superheated steam and using back-pressure steam turbines for the purpose of generating part of the usable electrical energy by converting the generated steam to process steam. According to Fig. 1, stages of CHP based on steam turbine include (1) producing superheat steam, (2) converting produced steam to required process steam by back-pressure steam turbine, (3) generating electrical energy, (4) use of steam in the process, and (5) return of condensate water to the boiler.

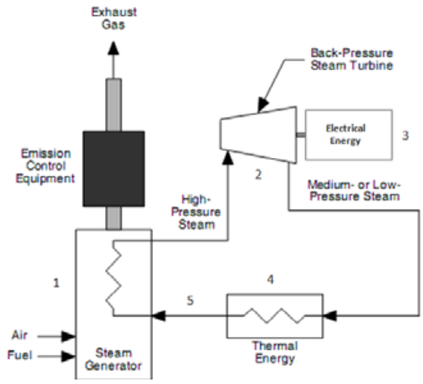

Fig. .1. Schematic performance of CHP System based on back-pressure Steam turbine [3]

During process of producing pulp from woods by chemical methods, Paper and Pulp Factories produce a byproduct called “Black Liquor”; and for recycling the chemical in it and because it has suitable thermal value, there are used a recovery boiler besides power boiler for recycling chemicals and producing steam required for processing; this may justify the cost of installation and launch of a CHP system in such industries [4]. Using black liquor as a fuel to produce steam, during the process of CHP can reduce CO_2 production up to 8% [5].

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The presentation of a vast analysis in the amount of consumption of heat and electricity by a factory is geared towards an attempt for the economical reduction in energy consumption and realizing existing potentials in the field of generation of electricity by the factory itself [6].

II. Specification of Factory under Study

The studied factory has the capacity for producing Kraft liner paper up to 500 tons per day by Kraft method and it needs 100.56 tons per hour of superheat steam for producing the same size of paper. For producing such rate of steam, factory uses power and recovery Boilers with specifications detailed in table I [7].

TABLE I
Technical Specifications of Equipments in Design Condition

Equipments	Specifications	Unit	Values
Power Boiler	Nominal Capacity	Ton/hr.	160
	Type of Fuel	Natural gas	
	Efficiency	%	68.84
Recovery boiler	Nominal Capacity	Ton/hr.	74
	Type of Fuel	Black Liquor and Natural Gas	
	Efficiency (Liquor Fuel)	%	68.84
	Efficiency (N.Gas Fuel)	%	65.88
Mono-stage Turbo Generator	Nominal Capacity	MW	15.4
	Mass of Input Steam	Ton/hr.	170
Damp Condenser	Nominal Capacity	Ton/hr.	60
Mill Power Demand	Electrical	Mw	17.235

According to designing conditions, the thermal value of natural gas is 38056 KJ/m^3 and thermal value of black liquor is 13500 KJ/kg. Specification of steam produced and processed is according to table II [7].

TABLE II
Specification of Steam Produced and Processed During Designing State

Steam Type	Specificaitons	Unit	Values
Superheated steam	Pressure	Kg/Cm^2	60
	Temperature	°C	445
	Mass	Ton/hour	100.56
Medium Pressure Steam	Pressure	Kg/Cm^2	12.2
	Temperature	°C	200
	Mass	Ton/hour	72.56
Low Pressure Steam	Pressure	Kg/Cm^2	3.3
	Temperature	°C	170
	Mass	Ton/hour	28
Condense Water From Process	Pressure	Kg/Cm^2	2.2
	Temperature	°C	110
Boiler feed water	Pressure	Kg/Cm^2	60
	Temperature	°C	185

In this mill the high steam pressure, following passage through back-pressure turbine, is changed into medium-pressure steam, part of which is consumed in the process, and another part, following another decrease in pressure by pressure reducing valves and being turned into low-pressure steam, is consumed in the process. Due to change in production process and degeneration, the conditions for utilization of the factory equipments are according to the description in table III [7].

TABLE III
Equipment Specifications Under Operation Conditions

Equipment Name	Specification	Unit	Values
Power Boiler	Max Production Capacity	Ton/hr.	110
	Portion of Steam production	%	69.6
Recovery boiler	Max Production Capacity	Ton/hr.	40
	Portion of Steam production	%	31.4
	Portion of Liquor Fueled State	%	70
	Portion of Gas Fueled State	%	30
	Efficiency (Gas Fueled)	%	65.88
Turbo Generator	Power Produced	MW	6.36
	Input Steam Mass	Ton/hr.	108
Electrical Energy	Produced	kwh	6060
	Purchased from Network	kwh	6000

As indicated in above table, steam turbo generator due to change in the input steam rate by change in the pulp production process and wear will result in sharp decline in efficiency. Therefore, for more power production during peak power grid, factory will increase its steam produced and this steam is higher than steam consumed and additional steam converts under average pressure to returned water by damp condenser after exiting from turbo generator. Turbo generator production rate curve in different steam mass under operation conditions is according to (1), and fig. 2,

$$Power\ (MW) = 0.0004\, m^{\bullet 2} + 0.0183\, m^{\bullet} - 0.0822 \qquad (1)$$

$$80tph \le m^{\bullet} \le 150tph$$

Where; $m^{\bullet}$ is rate of mass flow of steam input to boiler (Ton/hour) and Power is active power produced in the turbine (MW).

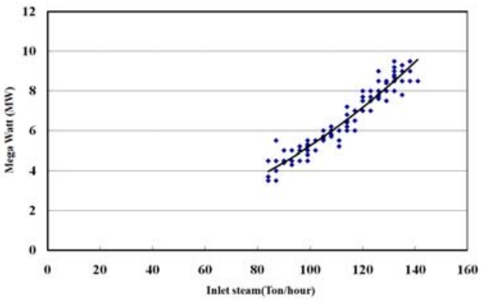

Fig. .2. Electric Power Curve of Turbo Generator based on Changes of Steam Mass

III. Governing Equations

A. Thermodynamic Equations

Principles required for thermodynamic analysis of thermal power plants and steam turbine as well as power production systems include mass and energy conservation laws, second law of thermodynamics and thermodynamic data accessible by tables. Power produced by steam turbine is calculated by (2) [8].

$$W = m^{\bullet}(h_{st} - h_w) \qquad (2)$$

Where, W is output power (Kw), $m^{\bullet}$ is mass flow rate based on ton per hour, h_{in} is turbine-input steam enthalpy and h_{out} is turbine-output steam enthalpy based on Kj/ton. Fuel used by boilers for steam production is calculated by (3) [8].

$$\dot{m}_{fuel} = \dot{m}_{steam} \frac{(h_{st} - h_w)}{\eta_{boiler} HHV} \quad (3)$$

Where, $\dot{m}_{st}$ is mean steam rate produced by boiler, h_w , h_{st} is enthalpy of steam and water feeding the boiler, HHV is high heat value of fuel consumed; η_{boiler} is thermal efficiency of boiler.

B. *Economic Equations*

The method of return on capital, in the science of engineering economy, is one of the standard methods of evaluating economic projects. In this method, the standard for evaluating the project is the duration of the return of investment. Projects with shorter period for return of capital are more attractive compared to those with a longer period. This method is particularly useful when comparing two or more projects with one another.

In this method, there are used investment costs during establishment for purchasing, installing and launching equipment and machineries used for project by which the project can be prepared for operation and production of product and or supply of services predicted for it. General equation for calculating the payback period is given by (4) [9].

$$-P + \sum_{j=1}^{n} (CF)_j = 0 \quad (4)$$

Where, P is initial cost and CF is financial process at the end of j_{th} year and if annual incomes at the end of any year are equal, payback period is given from (5).

$$n = P / CF \quad (5)$$

According to (4) and (5), payback period based on models provided in next part is calculated by (6):

$$n = \frac{(C_p + C_i)}{C_{ebt} + C_{est} + \Delta C_{ng} - \Delta C_{mt}} \quad (6)$$

Where, C_p is initial cost of equipping; C_i is cost of installation and launch; C_{ebt} is cost of power purchased from grid during time t, C_{est} is cost of power sold to the network during time t, ΔC_{ng} is increased rate of gas cost due to change in the working system, ΔC_{mt} is the increased cost of maintenance and repair due to model change.

C. *GHG Reduction Factor*

Cumulative reductions in greenhouse gases of power plants with natural gas fuel are estimated about 400-780 gCO_2eq/kwh [10]. The estimation of minimum reduction rate of GHG distribution is calculated by (7), for this factory:

$$\Delta C_{ei} = \Delta E * 0.4 \quad (7)$$

Where, ΔC_{ei} is GHG Reduction Rate (Kg), ΔE is Increased Electric Energy produced or change in the type of production technology and stable gas consumption rate (KWh).

IV. Modeling

For the purpose of modeling and analyzing this plant 12 different scenarios were considered using 4 steam turbine technologies, and 3 strategies of steam production. Table-4 deals with the steam turbine technology.

TABLE IV
Technology of Steam Turbines

Item	Technology of Steam Turbine
1	Mono Stage Back-pressure Turbine (HP/MP)
2	Back-pressure Turbine HP/MP+ Back-pressure Turbine MP/LP
3	Back-pressure Turbine HP/LP
4	Condensed Turbine HP/Cond.

In the first technology, the existing condition of the plant has been modeled. In the second technology, a back-pressure turbine MP/LP has been added to the existing state of the plant. In the third technology, replacing the existing turbine with a backpressure turbine HP/LP with the capability of cashing MP steam was performed. In the last technology, the replacement of the existing turbine with a condensing turbine HP/Cond., with the capability of cashing MP and LP steam was examined. Table V introduces the strategies for steam production in this factory.

TABLE V
Strategy of Steam Production

Item	Strategy of Steam Production
1	100% steam production by power boiler
2	Operation from recovery boiler under maximum conditions (producing 40 tons steam per hour with gas and black liquor fueled)
3	operation from recovery boiler under maximum conditions (producing 40 tons of steam per hour only by black liquor fuel)

In this analysis the produced steam mass was changed from the minimum permissible amount of 85 tons/hr. to the maximum allowable amount of 150 tons/hr., and the amount of electrical power generated and gas consumption were examined in different scenarios.

V. Results

According to analysis of different scenarios, under technologies applied for steam turbine and strategies for steam production, its results indicated as below. Fig. 3, indicates the diagram of change in the rate of power produced by different technologies, steam turbines based on changes in the mass of input steam.

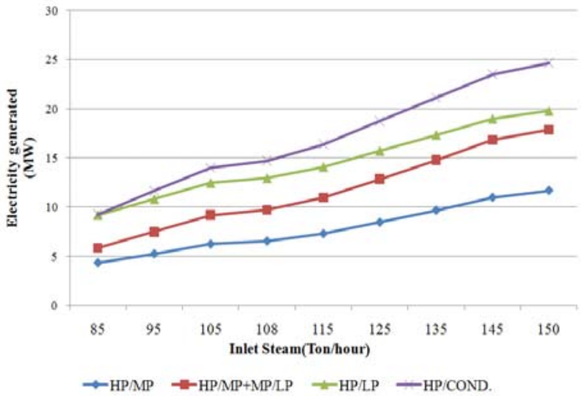

Fig. 3. Graph of changes in power generated in different technologies relative to steam mass

As indicated, all technologies in maximum input steam of 150 tons per hour has maximum power production, but best technology and maximum power production under the same conditions of input steam is using condensed turbine HP/Cond., by the possibility of sub cashing the steam MP and steam LP.

Fig. 4 indicates the diagram of changes in the rate of gas consumed for producing steam based on changes in the steam mass produced.

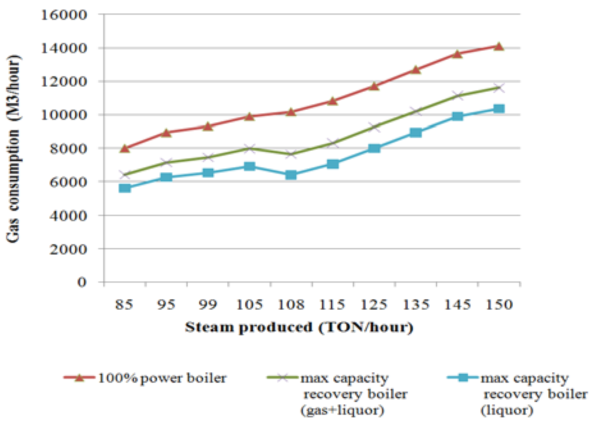

Fig. 4. Graph for changes in amount of gas consumption in different strategies for changes in mass of steam

As you can see, the best strategy for steam production and minimum natural gas consumption is using maximum capacity of recovery boiler under liquor-fueled state.

Economic analysis for benefiting from different technologies of steam turbine in maximum steam production is 150 ton per hours under steam production strategy using maximum recovery boiler under liquor-fueled state. Table VI indicates economic analysis conducted based on above mentioned conditions [11].

TABLE VI
Economic Analysis Results

Type of plan	HP/MP +MP/LP	HP/LP	HP/COND.	_
Steam turbine type	56B F/C	56BE F/C	60CXE2 F/C	_
Inlet steam(HP)	150	150	150	Ton/hour
Inlet steam(MP)	85.65	0	0	Ton/hour
MP Extraction	0	64.35	64.35	Ton/hour
LP Extraction	0	0	19.75	Ton/hour
Outlet steam	85.65	85.65	65.9	Ton/hour
Initial cost (C_P)	1770000	280000 0	3350000	Euro(€)
Cost of instalation (C_i)	177000	280000	335000	Euro(€)
Electrical power produced	17.86	19.8	24.66	MW
Electrical power consumed	12.06	12.06	12.06	MW
Marketable electrical power	5.8	7.74	12.6	MW
increased rate of gas cost due to change in the working system	3609	3609	3609	M^3/h
(ΔC_{ng})	630000	630000	630000	Euro(€)/year
(ΔC_{mt})	0	0	0	Euro(€)/year
(Cebt)	504707	504707	504707	Euro(€)/year
(C_{est})	538030	718017	1168878	Euro(€)/year
Operating hours per year	8000	8000	8000	hours
payback period time	4.7	3.2	1.9	year

The best scenario is using condensed turbine HP/ Cond. With maximum steam production to 150 tons per hour under strategy of maximum usage of recovery boiler under liquor fueled state.

VI. Conclusion

According to analysis under status quo of factory using mono-step back-pressure turbine HP/MP, based on receiving 150 tons per hour of superheat steam, factory can produce 11.6 MWh of power, while using the same steam size and Condensed Turbine HP/Cond., it is possible to produce 24.6 MWh of power.

To analyze the gas consumed under current conditions and proposed strategy, one can investigate the gas rate consumed under maximum power production in current conditions of 11.6 MW/hr based on 150 tons of steam and technology of condensed turbine HP/Cond. Based on producing 11.6 MWh based on 95 tons of steam per hour of input steam. Under current conditions, the strategy of using recovery boiler under liquor fueled and gas fueled conditions and strategy for producing steam using maximum capacity of recovery boiler under black liquor fuel individually.

Results indicate that under the scenario of using condensed turbine HP/Cond. With maximum steam produced 150 tons per hour under strategy under liquor fueled state it can be obtained maximum usage of recovery boiler followed by reduction of 41600 tons of CO_2 production (GHG) per year.

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