Biomass Based Cogeneration and Trigeneration for Effective Heat Recovery and Waste Management

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Abstract

Capacity addition in the generation sector and implementation of various energy management programmes in the consumption side, are possible solutions for the present energy crisis. But energy conservation is synonymous with energy generation. Conservation is cheaper than incremental cost of energy production. On the consumption side, industrial sector is the principal consumer of electricity followed by Commercial agricultural and domestic sectors. For energy conservation in industries, various measures have been proposed. Cogeneration which is also known as combined heat and power (CHP) has proved to be one of the promising energy management techniques, which offers an efficient method of producing electricity and useful thermal energy from a common source. In the present study the feasibility of steam turbine cogeneration for a plywood industry and a rice industry with power export are analyzed. An economic evaluation is made to see the viability of replacing the existing system by the cogeneration scheme. It is found that these two industries have a good potential for cogeneration and additional investment incurred for the new installation can be recovered within 3-4 years. Moreover, utilization of the waste wood which is generated by the industry greatly contributes to fuel saving and effective waste management.

Key Words: Industrial cogeneration, Plywood industry, Heat to power ratio, Back pressure steam turbine, Trigeneration.

1. Introduction

Cogeneration which is also known as combined heat and Power (CHP) is defined as the sequential generation of two different forms of useful energy from a single primary energy source, typically mechanical energy and thermal energy. Mechanical energy may be used to drive an alternator for producing electricity, or rotating equipment such as motor, compressor, pump or fan for delivering various services. Thermal energy can be used either for direct process applications or for indirectly producing steam, hot water, and hot air for dryer or chilled water for process cooling. The overall efficiency of energy use in CHP mode can be up to 80 per cent and above in some cases. Along with the saving of fossil fuels, cogeneration also allows to reduce the emission of greenhouse gases (particularly CO2 emission) per unit of useful energy output. The production of electricity being on-site, the burden on the utility network is reduced and the transmission line losses eliminated. If the utilization of biomass waste as fuel is also incorporated with CHP, it will lead to effective waste management, an additional ecological benefit.

Trigeneration is one step ahead of cogeneration that is the residual heat available from a cogeneration system is further utilized to operate a vapor absorption refrigeration system to produce cooling; the resulting device thus facilitates combined heat power and cooling from a single fuel input. Due to space limitations, trigeneration is not elaborated in this paper.

To study the feasibility of cogeneration in various process industries, plenty of researches have been reported. Technical energy measures in Swedish pulp and paper mills are investigated by Mollersten et al. (2003) [1] to study the potential of CO2 reduction and cost of CO2 reduction. Among the investigated measures, conventional technologies for electricity conservation and improved electrical conversion efficiency in existing systems for cogeneration of heat and power are identified as the most cost-effective alternatives that also have large CO2 reduction potentials. Wahlund et al. (2002) [2] presented a new approach for improving the performance of biomass-based cogeneration plants, a bioenergy combine. The system was a conventional biomass-based combined heat and power (CHP) plant in Sweden with integrated pellet production, where part of the CHP plant's heat is used for drying biomass feedstock for producing pellets. The total energy system of the bioenergy combine and the linked CHP plant is analyzed from a perspective of CO2 reduction and energy efficiency. The results show that the system has great potential for reducing CO2 and increasing the efficiency. Their study was extended (2004) [3]for a comparative study of CO2 reduction and cost for different bioenergy processing options to address the issue of which option Sweden should concentrate on to achieve the largest CO2 reduction.

A case study by Holanda and Balestieri (1999)[4] addressed questions involved in the energy generation and presented solid-waste burning as a possible alternative fuel for the future, especially in the context of cogeneration practice in which the thermal and electric energy are used primarily for the industries located in an industrial district. Two cogeneration schemes were proposed for the burning of municipal solid wastes, associated or not with natural gas, and their technical and economic feasibilities were examined.
Szklo et al. (2000) [5] developed the COGEN model to assess the eco-nomic potential of cogeneration ventures from the standpoint of the investor and guide incentive public policies. This model has been applied to two cases in Brazil; a chemical
plant and a shopping mall. A technical and economic feasibility study for a natural gas fueled cogeneration plant was conducted by Fantozzi et al. (2000) [6] in an important Italian pasta and animal feed factory. The layout analysis pointed out three main divisions; in each division electric and thermal users were pointed out and their effective energy consumption and power demand rate was monitored. A technical feasibility analysis was then carried out to determine the type and scale of the possible Combined Heat and Power (CHP) plants focusing on Internal Combustion Engines (ICEs) and gas turbine based power plants.
Berglin and Berntsson (1998) [7] had presented a thermodynamic analysis to study the feasibility of adopting black liquor gasification as alternative to the conventional heat recovery systems for

a cogeneration scheme in a pulp industry. Uran (2006) [8] had developed a model for thermo-economic analysis and optimization of cogeneration and noncogeneration as applied to a Croatian wood-processing industry. The study had presented results related to a decision on which system, cogeneration or noncogeneration, is optimal for the industry. Biezma and Duval (2001) [9] reported a 3.2MW wood fired cogeneration plant for a plywood industry in Pulau Borang, Palembang, Indonesia owned by PT Kurnia Musi Plywood Industries since 1995. His study provides the summary of some full – scale demonstration plants of biomass cogeneration implemented in Southeast Asia. A few of the many other works include , study on cogeneration in a sugar factory has been done by Raghu Ram and Banergy (2003) [10] and by Bhakshi (1993)[11], a textile industry by Tang and Mohanty(1996) [12] and Palanichamy et al. (2001) [13], an industrial park by Hsu (2002) [14], pulp and paper mill by Larson et al. (2002) [15] and palm oil mill by Husain et al. (2003) [16].

Recently Mujeebu et al. [17] presented annualized life cycle cost (ALCC) based feasibility study of cogeneration in a plywood industry. They also presented mathematical modeling for optimal cogeneration in a plywood industry [18] and a feasibility study of trigeneration for an Indian hotel [19]. Ravivardhan and Mujeebu [20] studied the viability of CHP for a rice mill. In the present study, study of Mujeebu et al. [17] is extended by introducing Heat to Power ratio technique for assessing the CHP options, Further, highlights of the works of Ravivardhan and Mujeebu [20] are also included. It is identified that the energy efficiency of the industries under study could be improved to a remarkable extent by implementing a steam turbine based CHP operating on biomass (waste wood and rice husk).

2. Case Study- 1

2.1. Profile of the industry

National wood products Ltd. is one of the leading plywood industries in South India, situated near Mangalore, Karnataka. Within a land area of 6 acres it has four manufacturing units each produce about 1000 block boards per day. All the four units operate in three shifts daily with a total of about 250 workers. Presently two thermic oil heaters and two steam boilers meet the process heat requirement of the industry. A stand by steam boiler is also provided. The electricity is purchased from the grid at the rate of INR 4/-(0.12 USD) per kWh. The steam boilers are supplied by Shanthi Boilers Sikendarabad, India; each has an efficiency of 80%. Table 1 shows the specifications of the boiler. The oil heaters are supplied by Thermax Bangalore, S. India and each has an efficiency of 70-80%. The oil heater specifications are given in table 2. Electrical parameters of one manufacturing unit are listed in table 3. Daily production details of one unit are shown in table 4. Fig. 1 shows the process layout of one manufacturing unit.

Table 1. Steam Boiler Specifications

Item	**Specification**
Overall length	3.5m
Inside diameter	2.25m
Design pressure	10.5 bar
Working Pressure	5 bar
Year of manufacture	1998
Total heating surface	110.9m
Total evaporation	2000Kg/h (From and at100^{0} C)
Maximum temperature	181^{0} C
Feed water	1000Kg/h
Fuel used	Waste wood
Fuel feed rate	4800-6000 Kg/h

Table 2. Oil Heater specifications

Item	**Specification**
Oil used	Therminol-55
Oil temperature	200-230^{0} C
Oil Pressure	2 bar
Specific heat of oil	3 kJ/kgK
Flow rate	60 m^3/h

Table 3. Electrical parameters of one manufacturing unit

Parameter	**Value**
Contract demand	150KVA
Demand charge	75% of contract demand (Rs.270/KVA per month)
Maximum load	160 kW
Average load	65 kW
Energy charge	INR- 3.5(USD- 0.11)/kWh
Time of use charge	INR -2.5(USD -0.08)/kWh
Power factor penalty	Nil
Average power factor	0.94

Table 4. Daily status of production per manufacturing unit.

Item	Description
Raw material	Silver wood, 15m^3
Finished product	Block boards 1000 Nos
Power requirement	65kW (average)
Process heat requirement	800kW(average)

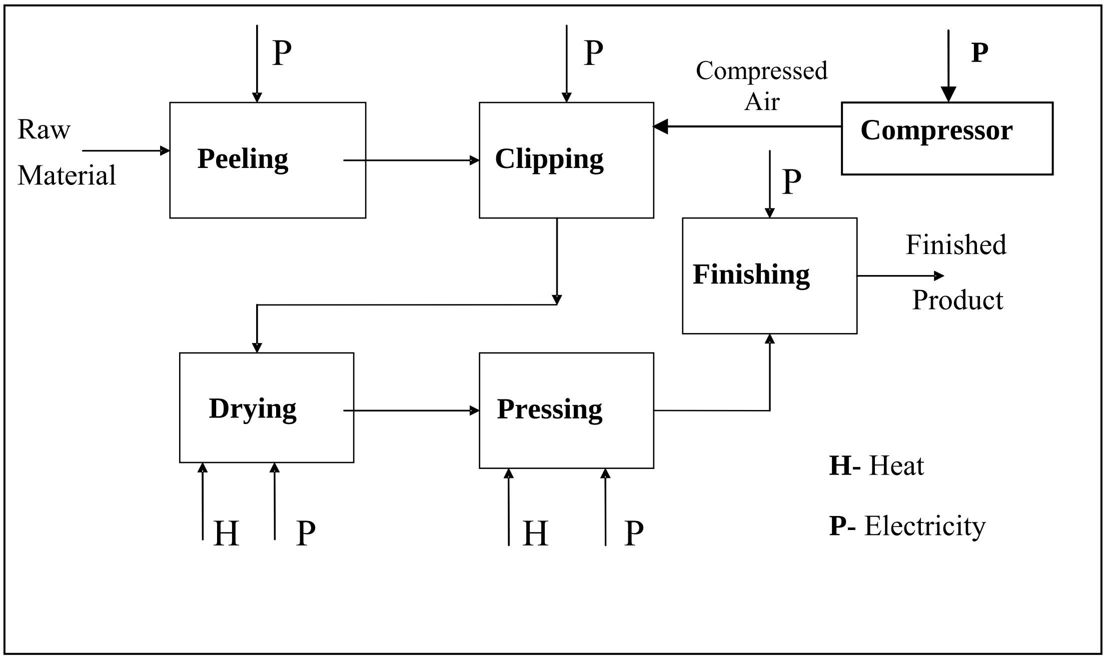

Fig.1. The process flow chart of one manufacturing unit

2.2. Electrical and thermal loads

Electrical and thermal load requirements of each manufacturing unit are measured on hourly basis for different days in a month, starting from 25-06-2006 including holidays, salary day, days with shortage of raw material and workers, etc. and the corresponding daily load curves are plotted to obtain the average daily load curve for the month. This is repeated for about ten months from June-2006 to March – 2007. An almost common trend is being observed in the power consumption pattern. A daily load curve was finally obtained as average of ten months which is shown in figure 2. The thermal load was found to be constant throughout.

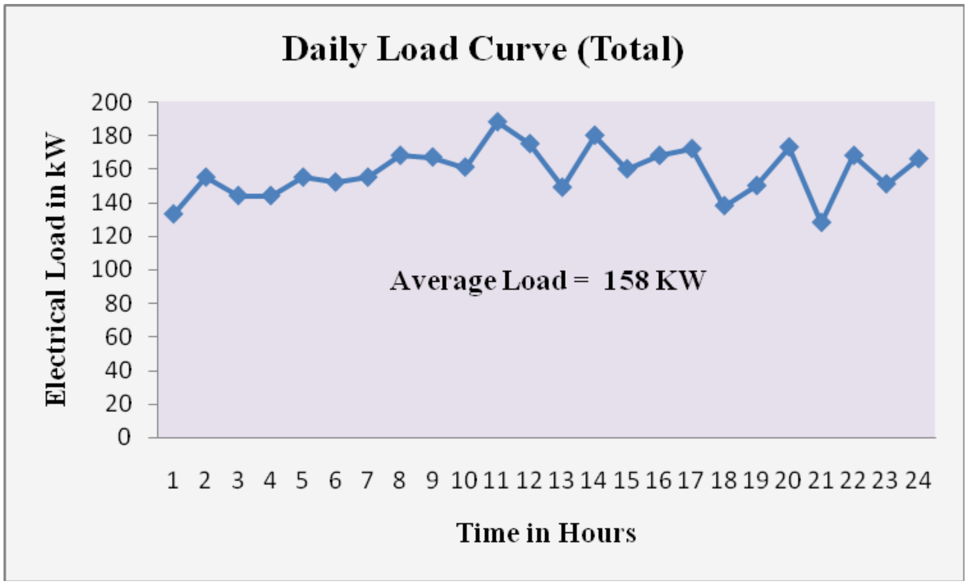

Fig. 2. Electric load curve for an average day

2.3. The Present Condition

If we look into the present situation, two boilers and two thermic oil heaters altogether consume waste wood as fuel at the rate of around 5 kg/s. Upon estimation the rate of energy release by the combustion of this quantity amounts to about 225000 kW, assuming the calorific value of waste wood as 45000 kJ/kg (from NPL website). But this input is utilized for meeting the heating load of 2056 kW only which means that the thermal efficiency of the plant is extremely poor. It is very important to note that the present thermal load could have been met by the two boilers with proper maintenance. The two oil heaters were procured recently without studying about its requirement. Hence it is obvious that the industry has a good potential for cogeneration in which case a single boiler with a higher capacity may meet both electricity and heating load. Moreover, there can be a scope for power export also.

2.4. Heat to Power Ratio

Heat to power ratio (H: P) is defined as the ratio of thermal energy to electricity required by the energy consuming facility. It can be expressed as:
H: P = KW_{th}/KW_e, KW_{th} = the thermal load in KW and KW_e = the electrical load in KW.

The conventional data for H: P and the expected overall efficiency of various cogeneration schemes are provided in table 5.

Table 5. H: P and efficiency for various cogeneration options

Cogeneration System	**Heat-to-power Ratio**	**Overall Efficiency %**
Back-pressure steam turbine	4.0 – 14.3	84-92
Extraction-condensing steam turbine	2.0-10.0	60-80
Gas turbine	1.3-2.0	70-85
Combined cycle	1.0-1.7	69-83
Reciprocating engine	1.1-2.5	75-85

Based on the classification in table five a back pressure steam turbine cogeneration is suitable for the industry as it has a heat power ratio of 13.0.

3. The Proposed Steam turbine cogeneration

3.1. Description of the system

A part of steam generated in the boiler is directly utilized for the process heat requirements of three manufacturing units, the remaining part is expanded in the turbine to produce electricity and the turbine exhaust steam is further used in the fourth unit and pumped to the mixing chamber for the next cycle. As there is enough waste wood generated by the plant, it is more than sufficient to be utilized as fuel. The schematic of the system with details of pressure, temperature and mass flow rate of steam entering each unit, total electric load etc. are shown in figure 3.The installation cost of steam turbine cogeneration system as obtained from the manufacturer is shown in table 6. Out of the one megawatt electricity produced, a maximum of 200kW is reserved for the plant and the rest can be sold to the grid, which would be an attractive source of earning for the industry.

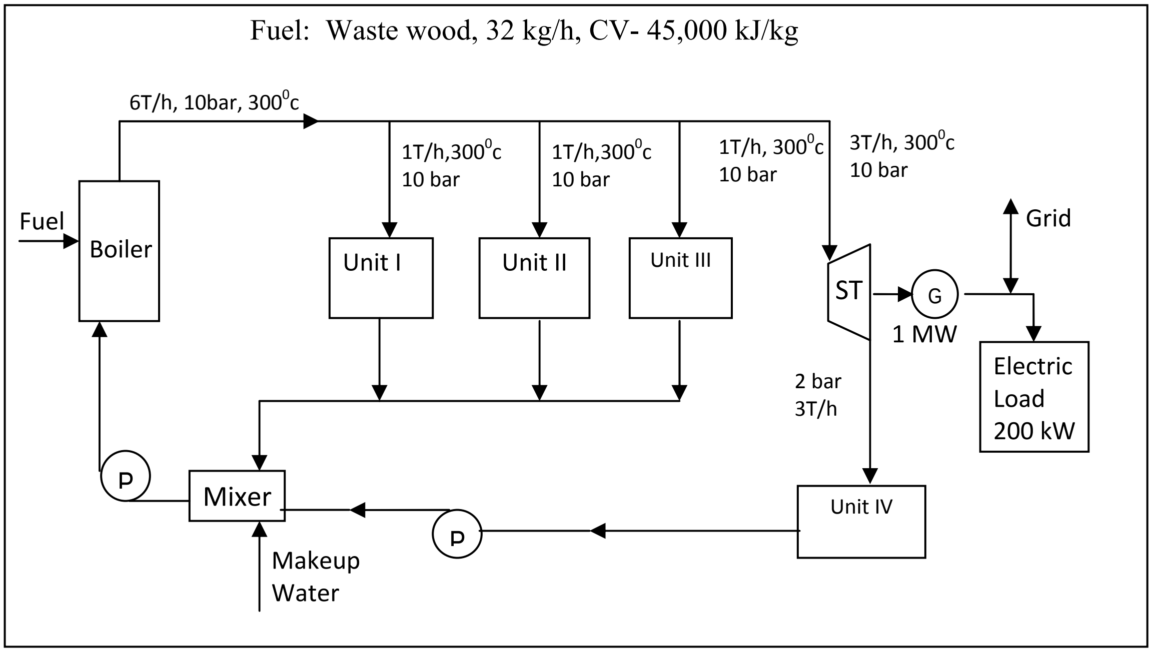

Fig.3. Schematic of the proposed steam turbine cogeneration system

Table 6. Installation cost of steam turbine system
(Source- Shanthi Boilers, Sikandarabad, India.)

Item	**Nos**	**Cost(Millions)**	
		INR*	**USD***
Steam boiler, 6T/h,10bar, 300^0C	1	5.0	0.150
Steam turbine, 1MW	1	7.5	0.225
Boiler feed pump	2	2.0	0.060
Steam line		3.0	0.090
Water tank	2	0.5	0.015
Civil works		4.0	0.120
Boiler controls		0.5	0.015
Miscellaneous		0.7	0.021
Total		**23.2**	**0.696**

*INR – Indian Rupees, USD – US Dollars

3.2. Evaluation Methodology

A steady state operation and linear behavior in the performance of steam turbine boiler and other equipments are assumed for all calculations. The following basic thermodynamic relations (eq. 1 to eq. 5) are used for calculating relevant parameters such as boiler capacity, turbine work, heat input, fuel consumption and energy utilization factor (of the proposed cogeneration system).

Turbine work $W_T = \frac{W_e}{\eta_t \eta_g}$ (1)

where, We = the total electrical power demand (known), η_t = mechanical efficiency of the turbine and η_g = generator efficiency.

Also Turbine work $W_T = m_s\,(\Delta h)$ (2)

where Δh = the difference in specific enthalpy of the steam while expanding through the turbine, and m_s= the mass flow rate of steam.

The fuel consumption is calculated by using the following relations (3&4)

Heat input $Q_i = \frac{W_e}{\eta_{th}\eta_c}$ (3)

where ηth = thermal efficiency of the plant and η_c = combustion efficiency

Also heat input $Q_i = m_f\,CV$ kW (4)

where, m_f = fuel consumption in kg/s, and CV = calorific value of fuel in kJ/kg.

The energy utilization factor of the cogeneration system (EUF)

$EUF = \frac{E_{th}+E_e}{Q_i}$ (5)

Where, E_e = Energy utilization as electricity and E_{th} = Thermal energy utilization

The relations used for economic analysis are as follows:

Maintenance Cost (MC) = Equipment starting and shutdown cost + Labor cost+ Fuel cost (7)

The simple payback period (SPP) = $\frac{Investment}{Annual\ Saving}$ years (6)

The assumptions made for the analysis are summarized in table 7.

Table 7. Summary of assumptions made

Sl. No.	Parameter	Assumed Value
1	Combustion efficiency	80%
2	Turbine efficiency	85%
3	Compressor efficiency	85%
4	Electricity selling charge	INR -2.5(USD -0.08)/kWh
5	CV of the fuel	45000kJ/kg

3. Results and Discussion

The results of economic evaluation are summarized in table 8. It is interesting to see that the proposed cogeneration system will save the electricity purchase cost INR. 42.8 millions (USD 0.084) besides providing a revenue of INR 3.2millions (USD 0.10) per year through power export. Thus the total saving in annual operating cost would be INR 67%. The additional investment needed for installation of cogeneration plant is found to be INR 13.2 millions (USD 0.4) after deducting the resale value of the existing equipments, yielding a SPP of about 4 years which is acceptable

Table. 8. Comparison of Steam turbine Cogeneration with the existing facility

Cost components (Cost in Millions)	**Existing Facility**		**Steam Turbine Cogeneration**	
	INR*	**USD***	**INR***	**USD***
Fuel cost	Nil	Nil	Nil	Nil
Maintenance cost	3.00	0.09	4.8	0.14
Electricity purchase cost	2.80	0.084	Nil	Nil
Earning from power export	Nil	Nil	3.2	0.10
Net annual operating cost	4.8	0.15	1.6	0.05
Annual saving			**3.2**	**0.10**
Total cost of installation			23.2	0.70
Resale value of the existing equipments			10.0	0.30
Additional investment			**13.2**	**0.40**
Simple payback period	**4.125 years**			

*INR – Indian Rupees, *USD – US Dollars

4. Case Study -2

4.1. About the Industry

Maruthi Rice Mill, the industry under case study is a medium level unit in south India near Bangalore. The profile of the industry is summarized in table 9. The steam is utilized for the partial cooking of the rice paddy and to meet all of the drying requirements. The sequence of processes involved in the conversion of paddy into clean and dry full rice grains is shown schematically in Fig.4. The fuel used is rice husk which is available plenty as waste. The electricity is purchased from the grid.

Table 9. Details of Maruthi Rice Mill

Sl. No.	Item	Details
1	Paddy as input	400 bags per day
2	Rice as output	350 bags per day
3	Type of boiler	Fire Tube (KVR) Boiler
4	Boiler Capacity	1Ton, 2.5 bars, sat. steam
5	Fuel Consumption	385kg/h
6	Total workers	20
7	Land area	1 acre
8	Maximum electricity demand	100kW
9	Connected load	High Tension, 400V, 65 A

4.2. The Proposed System

In the proposed scheme, a steam turbine topping cycle is being suggested which primarily produce electricity and the turbine exhaust steam may be effectively utilized for heating needs as shown in Fig. 5. As the electricity demand is fully met, the industry becomes independent of the grid. According to the capacity of the proposed system, it is found that there is a chance of excess electricity production in its full time operation. This can be sold to the grid hence forms an additional source of income. The additional fuel requirement may be met by purchasing rice husk from the neighboring rice mills, which is found feasible. The selling price of electricity to the grid is Indian rupees INR 2.50 (0.075 USD) per kWh, as fixed by the state electricity board. A contract with the board is to be made for this deal.

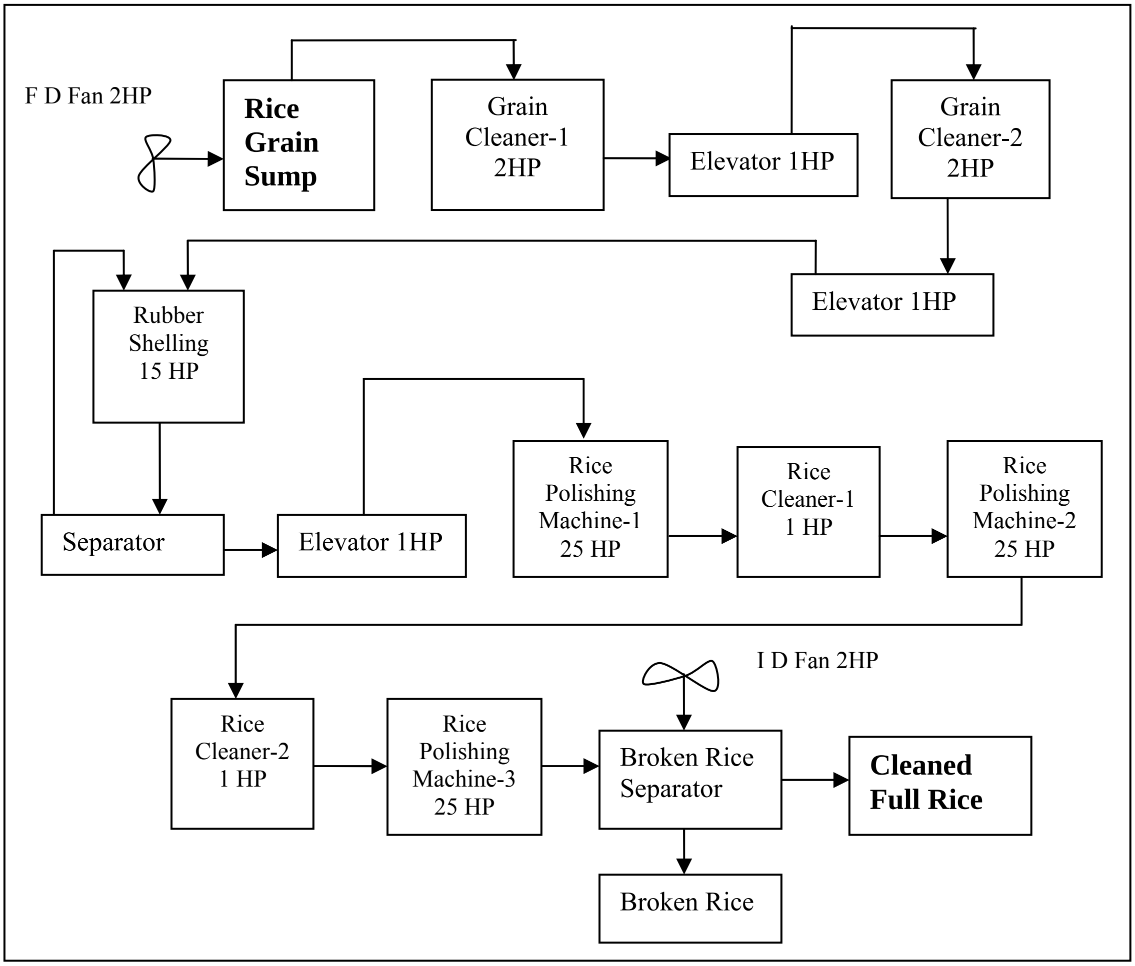

Fig. 4. Process flow diagram of Maruthi Rice Mill

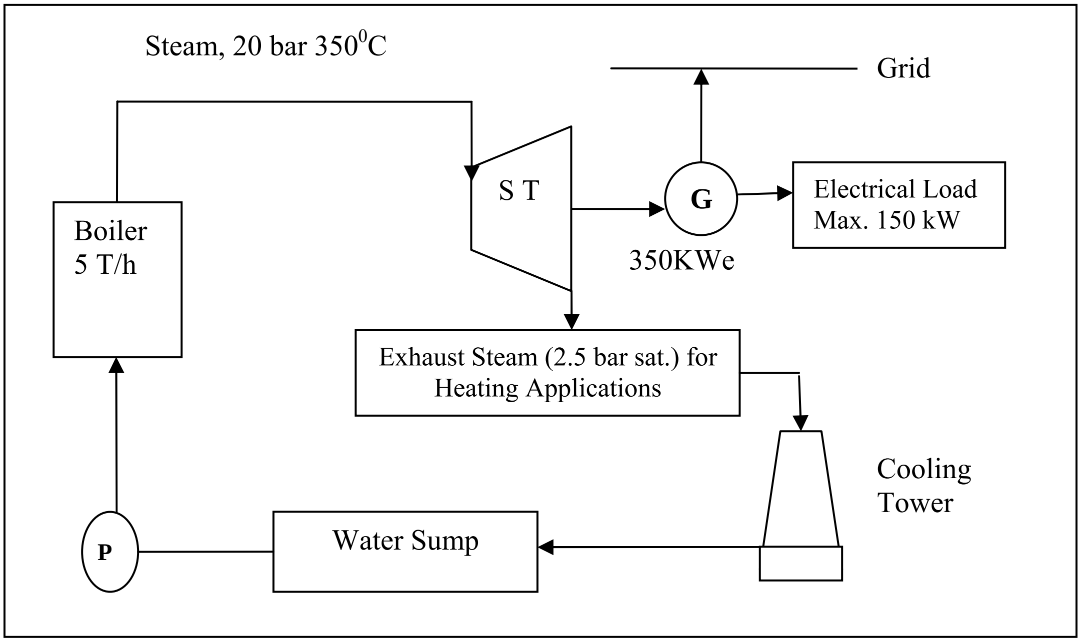

Fig.5. Schematic of the proposed cogeneration system.

5. Results and Discussion (rice mill)

A thorough economic analysis is made by taking into account the additional cost of installation, excess fuel purchase, income from power export, savings through the use of self electricity etc. The installation cost split up and summary of economic analysis is presented in tables 10 and 11. The installation cost is kept at its maximum for the purpose of analysis. It is clear from the result that the industry has a good potential for cogeneration and as the payback period is very short the proposed scheme can be implemented without any financial risk.

Table 10. Installation cost of the proposed system
(Universal Instruments Co. Pvt. Ltd. Bangalore, South India)

Item	**Cost in Millions**	
	INR*	**USD***
Steam Boiler, 2Tons	2	0.06
Turbine –Generator assembly	7	0.21
Accessories	0.16	0.005
Cooling Tower	0.02	0.0006
Water Tank	0.1	0.003
Miscellaneous	0.5	0.015
Total	**9.78**	**0.2936**

*INR = Indian Rupees, *USD = US Dollars

Table 11. Annual saving

Item	**Cash in Millions**	
	INR	**USD**
Earning from power export	5.411	0.16233
Saving through self electricity	1.28	0.0384
Less cost of excess fuel	1.462	0.04386
Net saving	**5.29**	**0.1587**

6. Conclusion

In the first case study, the viability of cogeneration system with power export for a typical plywood industry is analyzed with different options. It is found that the industry has a good potential for cogeneration and steam turbine cogeneration is viable in both technical and economic perspectives. The proposed scheme can provide attractive saving (67%) in annual operating cost with a simple payback period of 4years.

In the second study, the feasibility of steam turbine based captive power plant with cogeneration for a rice mill is analyzed. It is found that if the existing facility is replaced by the proposed scheme with power export an appreciable saving in money can be achieved.

Apart for the benefit of energy management, in both the cases, the utilization of waste as fuel significantly contributes to waste management also. Excellent works are underway in the area of CHP and trigeneration, but most of the important works are left without citation due to page limitation. Though cogeneration is not a new idea it can contribute a lot in the area of energy conservation and management. Unfortunately most of the industries are still either unaware of its benefits or reluctant to take a risk to implement this technique. The industry institute interaction is to be highly enhanced to educate the industrialists about the benefits of these techniques. The trigeneration area is to be explored further.

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