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Modification of Co-Generation Plant in a Sugar Cane Factory for Reduction of Power Deficit

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Abstract: This study outlines work on the modification of co-generation plant in a sugar cane factory for reduction of power deficit. These modifications, which tested though a sample 6000 TCD sugar cane factory, contain minimization of process steam demand and also high-pressure steam production, using high-pressure boilers which coupled with condensing-extraction steam turbines as option 1 and biomass integrated gasification as option 2. By these modifications, the additional revenue for sugar industry by generating surplus power and supplying to national grid could be possible. Applying the suggested modifications on the sample factory achieved 4 and 22.4 million USD monetary benefits for options 1 and 2, respectively. Because of the required investment for options 1 was 16 million USD and for option 2 was 179 million USD, the investment had an attractive simple payback period of 4 years for option 1 and 8 years for option 2. Thanks to the increased amount of agricultural residues available for power production, the higher efficiencies in conversion and to a lesser extent, the avoided emissions as a result of less sugar cane burning, the emissions of CO_2, greenhouse gases and particulates would be significantly reduced.

Key words: Bagasse, gasification, co-generation plant, steam turbine, process steam

INTRODUCTION

The energy is supplied to the sugar cane factory mainly as fuel or bagasse to the power house and bagasse drying plant. The power house typically incorporates a steam boiler and a back-pressure steam turbine. When burning fuel in the boiler furnace, live steam is produced and supplied to the turbine. The turbine drives an electrical generator which generates power for the factory and the steam leaving the turbine exhaust flows to the heating equipment for sugar manufacture. This is known as co-generation of heat and power or Combined Heat and Power (CHP) (Asadi, 2007; Hugot, 1986; Mathur, 2004; Smouse *et al*., 1998). In conventional sugar factories, the demand for low pressure steam is 0.4-0.6 kg of steam per 1 kg of cane and the simple medium pressure steam cycle is used for simultaneous heat and power generation in the co-generation plant (Asadi, 2007; Van der Poel *et al.*, 1998).

In contrast to the many industries, the sugar industry can generate surplus power by modification of their co-generation plants. Co-generation option has been adopted in many of the sugar mills, with substantial additional revenue for the mills. This also contributes to serve the national cause in a small way, by bridging the demand-supply gap (Purohit, 2009; Van der Poel *et al*., 1998).

When steam demand in the process is high and the simple medium pressure steam cycle is used, surplus power generation is difficult. However, by minimization of the process low pressure steam demand and using other cycles such as high pressure steam cycle and Biomass Integrated Gasification-Combined Cycle (BIG-CC), the power deficit can be reduced. In other words, by improvement of the co-generation plant in sugar factories, selling additional power to the national grid will be possible (Asadi, 2007; Purohit, 2009). This also offers an excellent opportunity for the sugar mills to generate additional revenue (Mbohwa and Fukuda, 2003; Smouse *et al*., 1998). For minimization of the process low pressure steam demand to add power production in the co-generation plant, replacement of steam driven mill drives with electric DC motors, as a major process steam consumer, should be considered.

The aim of this study is modification of co-generation plant in sugar cane factories for increasing the power to heat ratio and supplying additional power to the national grid. For this study, in addition to suggest a method for minimization of the process low pressure steam demand, two options are considered to increase the power to heat ratio in the co-generation plant of sugar cane factories; use of high pressure boilers which coupled condensing-extraction steam turbines as option 1 and use of the Biomass Integrated Gasification-Combined Cycle (BIG-CC) as option 2. These two methods as well as the technique for minimization of the process steam demand have been tested through a sample 6000 TCD sugar cane factory.

MATERIALS AND METHODS

For generation surplus power in a sugar cane factory, the low pressure steam demand of the plant should be minimized as the first step. In this study, it has been done by replacement of low efficient steam driven mills with the more efficient ones or with electric motors. In the second step, increasing of the power to heat ratio in co-generation plant of the sugar cane factory has been considered. This improvement could be achieved by using the two options as follows:

Use of High Pressure Boilers and Condensing-Extraction Steam Turbines

Figure 1 shows the power to heat ratio for a back-pressure steam cycle, as a function of live steam pressure. Increasing pressure are accompanied by increasing temperatures, which however are limited to about 530°C, in order to permit the use of less expensive ferritic steel as a material for the boiler super-heater. This limits the steam pressure because of the thermodynamic properties of steam. To avoid erosion problems in the turbine, live steam pressure of 80-85 bar is the maximum pressure which can be allowed today in a power house based on the simple steam cycle employing a back-pressure

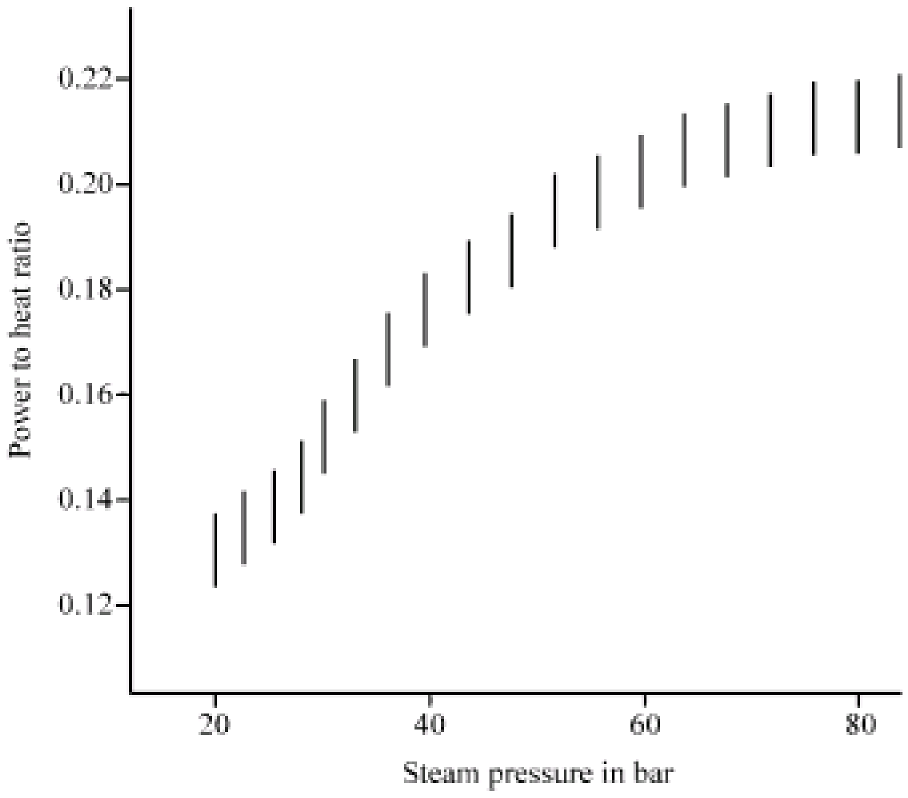

Fig. 1: Ratio of power generated to heat supplied from the back-pressure steam cycle, as a function of live steam pressure (Van der Poel *et al*., 1998)

turbine (Van der Poel *et al*., 1998). At the live steam temperature of 525°C, the ratio of power generated to heat supplied is about 0.20-0.23. In the contemporary energy-efficient sugar factories, the ratio of power demand to heat demand has already reached this level and if the heat demand is further reduced, then the simple steam cycle can no longer supply enough power. Although, the power deficit can usually be covered by power imports from the external grid, in most countries the power tariffs prevent such a solution from being economical.

In this study, use of high pressure boilers which coupled condensing-extraction steam turbines has been considered as option 1 to increase the power to heat ratio in the co-generation plant of the sample sugar cane factory.

Use of the Biomass Integrated Gasification Combined-Cycle (BIG-CC)

Various modification of the steam cycle that could solve the power deficit problem (Urbaniec, 1989) are uneconomical under the conditions of the sugar cane industry. Better economic prospects arise from the application of a Biomass Integrated Gasification-Combined Cycle (BIG-CC) system. For the same supply of process heat, such a cycle can produce more power than the simple steam cycle and its power to heat ratio can attain values above 0.30. Actually, in the sugar cane industries, after satisfying its own steam and electricity demand, supplies an average of 15 kWh t^{-1} of electrical energy to the national grid. With the BIG-CC technology, an average of 100 kWh t^{-1} or more can be generated, if the conditions of low process steam consumption and reduced factory power consumption are imposed.

For installing the BIG-CC plant in sugar cane factories, a gasified biomass burning gas turbine is needed. A gas turbine includes a compressor which raises the pressure of atmospheric air to about 3-5 bar and then delivers it to a combustion chamber where the gasified biomass is burnt as the fuel. With the materials presently available for gas turbine components, the combustion temperature must not exceed 1000°C which necessitates relatively high air surplus, resulting in 12-16% oxygen content in the combustion gas. The gas subsequently expands in a turbine, which is mounted on the same shaft as the compressor. The rotational velocity may be as high as 10,000 min^{-1}, so there is usually a reducing gearbox between the turbine compressor set and the electrical generator. The gas temperature in the turbine exhaust is 430-550°C.

Among various possibilities for application of the Biomass Integrated Gasification-Combined Cycle (BIG-CC) in the sugar cane factory, one solution is most cost-effective. This solution is shown schematically in Fig. 2. The power generated in the gas-turbine set alone can be 600 to 700 kWh/10 ton

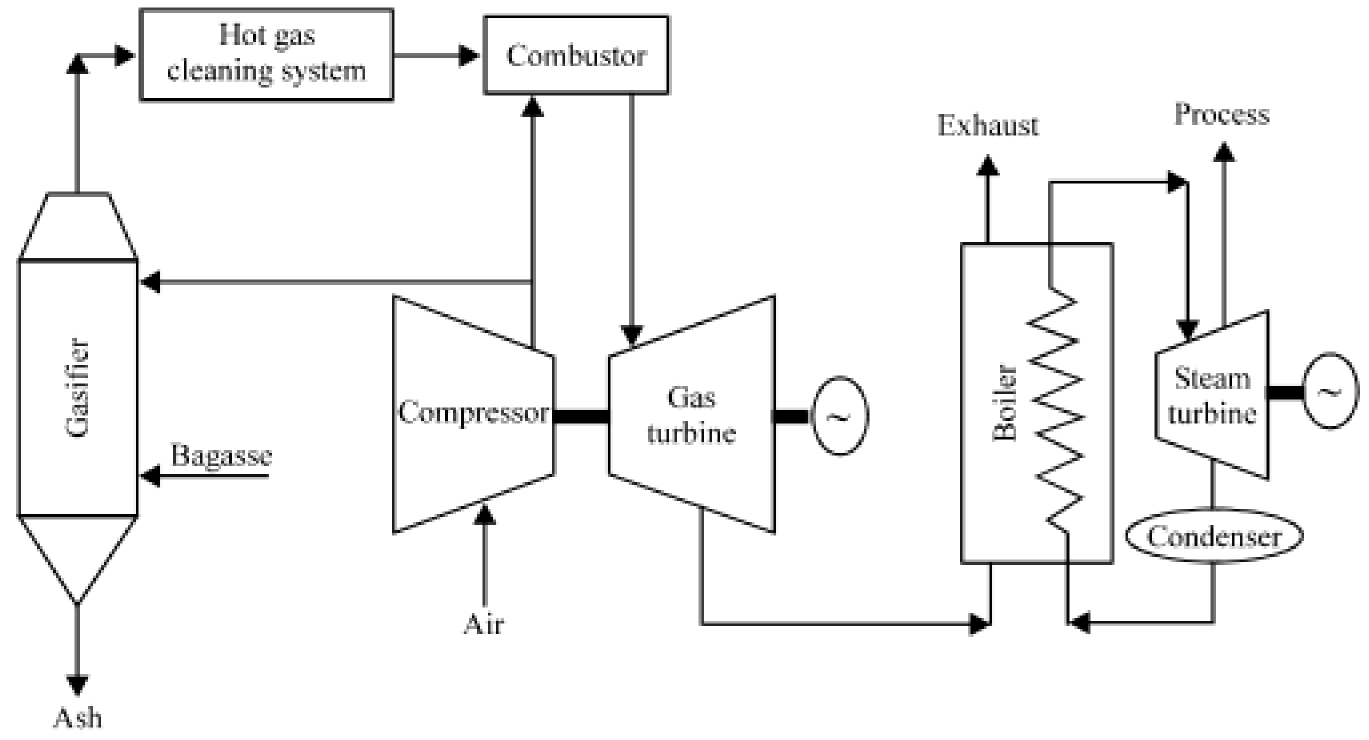

Fig. 2: Scheme of the Biomass Integrated Gasification-Combined Cycle (BIG-CC)

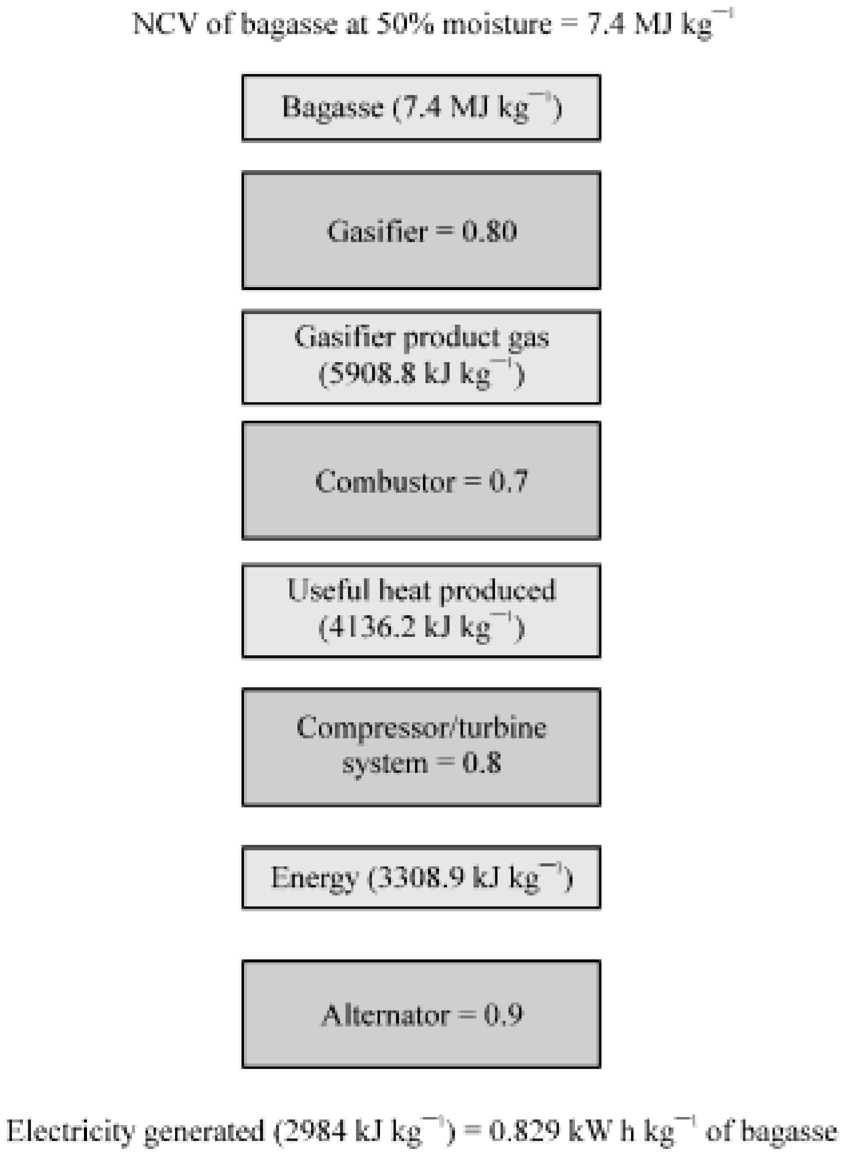

Fig. 3: Energy output from each stage of the BIG-CC

steam supplied from the boiler. In this cycle, bagasse is burnt in a gasifier to produce a combustible gas. The gas is then cleaned before being fed to the combustor. The air/gas mixture is burnt in the combustor to produce hot combustion gases which is conveyed to the gas turbine to generate power. The exhaust of the gas turbine is fed to a Heat Recovery Steam Generator (HRSG) to raise steam. The steam produced is expanded in a steam turbine to generate more power and process steam, at the required pressure and temperature, is extracted from the turbine (Higman and Van der Burgt, 2008; Kirubakaran *et al*., 2009).

The energy output from each stage of the BIG-CC is shown Fig. 3. Appropriate efficiencies for the different equipment were assumed, based on woody biomass and that gas cleaning is achieved. From the energy balance, some 829 kWh t^{-1} bagasse can be generated from the gas turbine (Ramjeawon, 2008). This energy balance excludes the output from the steam turbine when operating as a combined cycle. Based on the energy balance, overall conversion efficiency on the Net-Calorific-Value (NCV) of bagasse to useful heat of more than 40% is possible.

In this study, use of the Biomass Integrated Gasification Combined-Cycle (BIG-CC) has been considered as option 2 to increase the power to heat ratio in the co-generation plant of the sample sugar cane factory.

RESULTS AND DISCUSSION

A typical mill was used as a reference. This typical mill milled 6,000 tonnes per day. This sample sugar mill, similar to mills throughout the world, has process steam requirements of approximately 500 kg of steam per tonne of cane processed. The power requirement of the plant during the sugar-season was met by the internal generation and during the non-season from the grid. The sugar cane factory balanced is presented in Fig. 4.

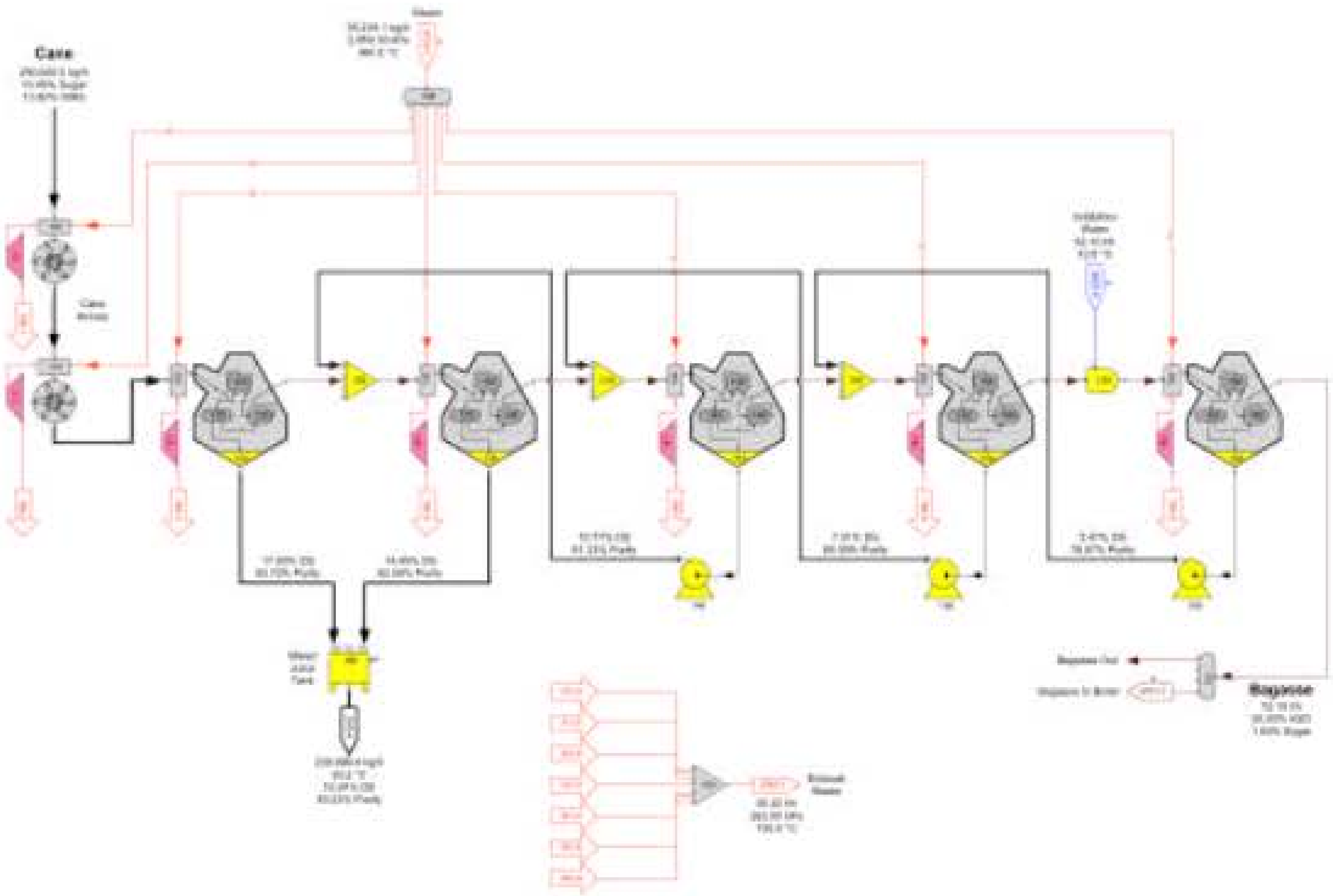

Fig. 4: The sample cane factory balanced

The sample sugar factory is under operation on 219 days per year (season) and is shut down on other days of the year (off-season).

The sample sugar cane factory had the following equipment in the co-generation plant:

- Boilers - 2 numbers of 18 TPH, 12 ATA
  2 numbers of 29 TPH, 15 ATA
  1 numbers of 50 TPH, 15 ATA
- Turbines - 1 number 2.5 MW
  1 number 2 MW
  1 number 1.5 MW
- Mill drives - 6 number 750 BHP steam turbines
  1 number 900 BHP shredder turbine

For increasing the power to heat ratio, the modifications on the co-generation plant of the sample sugar factory are done in the following two phases.

Phase 1: Replacement of Steam Driven Mill Drives with Electric DC Motors

Conventionally, steam turbines are used as the prime movers for the mills, in a sugar industry. These steam turbines are typically, single stage impulse type turbines having about 25-30% efficiency (Hugot, 1986; Mathur, 2004).

The recent installation of commercial co-generation system, with provision for selling the excess power to the grid, has made the generation of excess power in a sugar mill, very attractive. One of the methods of increasing the co-generation power in a sugar mill, is to replace the smaller low efficiency mill turbines, with better efficiency drives, such as, DC motors or hydraulic drives. The power turbines (multi-stage steam turbines) can operate at efficiencies of about 65-70%. Hence, the equivalent quantity of steam saved by the installation of DC motors or hydraulic drives can be passed through the power turbine, to generate additional power.

This replacement can aid in increase of net saleable power to the grid, resulting in additional revenue for the sugar plant. This case study highlights the details of one such project, implemented in a 6000 TCD sugar cane plant.

Previous Status

To multiple number of smaller capacity a 6000 TCD sugar mill had six numbers of 750 HP mill turbines and one number of 900 HP shredder turbine. The average steam consumption per mill (average load of 300 kW) was about 7.5 TPH steam at 15 ATA. The steam driven mill drives had an efficiency of about 35%, in the case of single-stage turbine and about 50%, in the case of two stage turbines. The plant team was planning to commission a commercial co-generation plant. This offered an excellent opportunity for the plant team to replace the low efficiency steam turbine driven mills, with DC motors or hydraulic drives and maximize the co-generation potential. The plant team contemplated the replacement of the steam driven mills with electric DC motors, along with the commissioning of the co-generation plant.

Concept of the Project

The conventional single stage impulse type steam turbines have very low efficiencies of 35%. Hence, the steam consumption per unit of power output is very high.

A single high capacity steam turbine is more efficient as compared steam turbines. Hence, the steam can be passed through the larger capacity steam turbine to generate more saleable power.

The latest drives, such as, DC drives and hydraulic drives have very high efficiencies of 90%. The steam saved by the installation of DC drives, can be passed through the larger capacity power turbines of higher efficiency (about 65-70%), to generate additional saleable power.

The steam turbine mill drives were replaced with DC drives, once the co-generation plant was commissioned. The modifications carried were as follows:

- Four numbers of 900 HP and two numbers of 750 HP DC motors were installed in place of the six numbers of 750 HP mill turbines
- Two numbers of 1100 kW AC motors were installed for the fibrizer, in place of the single 900 HP shredder turbine

The implementation of the project can be completed in 24 months.

Benefits Achieved

The comparative analysis of the operational parameters before and after the modification is presented in Table 1.

Table 1: The comparative analysis of the operational parameters before and after the modification

Parameters	Steam turbine	DC drive
Main drive efficiency (%)	35.00	90.00
Overall system efficiency (%)	26.60	39.50
Steam input/kW h of power delivered		
To the mill (kg)		
At 15 ATA	25.00	16.83*
At 65 ATA	-	7.97*
Steam consumption per mill (average load of 300 kW) (TPH)		
At 15 ATA	7.50	-
At 65 ATA	-	2.39*
Saving in steam (TPH)	-	5.11
Equivalent saving in power (kW)	-	850.00

*The steam consumption indicated, is the equivalent steam consumption in a power turbine, for generation of additional power

The equivalent saving in power (850 kW/mill) by the implementation of this project, can be exported to the grid, to realize maximum savings.

Phase 2: Modification of the Co-Generation Plant

By generating steam at 65 bar/421°C, sufficient electric and mechanical power (using back-pressure turbines) to run the plant is achieved and nearly all bagasse produced is consumed. Thus, fuel availability and power and thermal energy requirements are balanced. The boilers normally have low efficiency, the reason being that there is little incentive to improve the energy conversion system as institutional barriers have not given sufficient incentive to produce more electric energy than required in-house and because bagasse is considered to be a waste material, any excess bagasse when entering the off-season will require that it be disposed of at cost.

For increasing the power to heat ratio in the co-generation plant of the sample sugar factory, two options are considered as follows:

Option 1: Use of High Pressure Boilers and Condensing-Extraction Steam Turbines

The plant went in for a commercial co-generation plant as Option 1. In this option, the old boilers and turbine should be replaced with high-pressure boilers and a single high capacity turbine. The new turbine installed will be an extraction-cum-condensing turbine. The new energy flow chart for this option has been shown in Fig. 5.

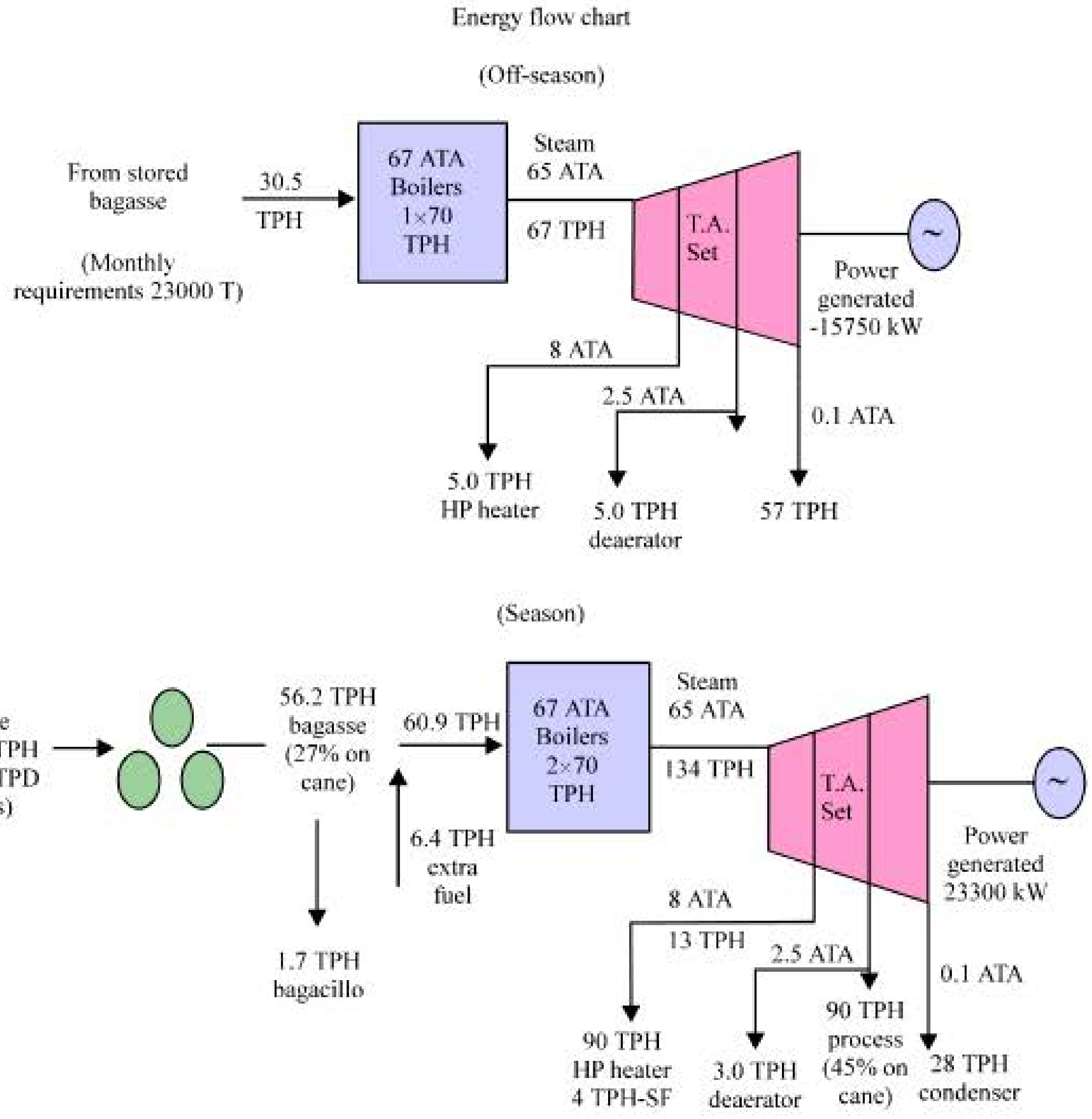

Fig. 5: Energy flow chart (Off-season and season) for option 1

Table 2: Summary of the benefits achieved in option 1

Parameters	Units	Previous status (Low pressure boiler system)	Option 1 (High pressure boiler system)
Bagasse quantity	TPH	1.0	1.0
Steam quantity	TPH	2.1	2.2
Steam pressure	ATA	14.0	65.0
Power generation	kW	158.0	382.0
Extra power generated	kW	-	224.0
Steam quantity available for process	TPH	2.1	2.2
Steam pressure available for process	ATA	1.6	2.5
Steam on cane	%	52.0	45.0

A provision is also made, form exporting (transmitting) the excess power generated, to the state grid. The mill steam turbines should be replaced with DC drives. The details of the new boilers, turbines and the steam distribution are as indicated below:

- Boiler - 2 number of 70 TPH, 67 ATA
  Multi-fuel fired boilers
- Turbines - 1 number of 30 MW turbo-alternate
  (Extraction-cum-condensing type)
- Mill drives - 4 numbers of 900 HP DC motors
  2 numbers of 750 HP DC motors
  2 number of 1100 kW AC motors

In this option, two high capacity high-pressure boilers and a 30 MW turbine should be installed in place of the old boilers and smaller turbine. While selecting the turbo-generator, it is decided to have the provision for operation of the co-generation plant, during the off-season also. This could be achieved, by utilizing the surplus bagasse generated during the season, as well as by purchasing surplus bagasse, from other sugar mills and biomass fuels, such as, groundnut shell, paddy husk, cane trash etc. The shortfall of bagasse during the off-season is a problem initially. The purchase of biomass fuels from the nearby areas and the use of lignite solved this problem. The entire project can be completed and commissioned in 30 months time. The installation of high-pressure boilers and high-pressure turbo-generators has enhanced the power generation from 9 to 23 MW. Thus, surplus power of 14 MW is available for exporting to the grid.

The summary of the benefits achieved in option 1 (expressed as value addition per ton of bagasse fired) is shown in Table 2.

The following operating parameters can be achieved in option 1:

- Typical (average) crushing rate = 6000 TCD
- Typical power generation
  - During season = 5,18,321 units day^{-1}
  - During off-season = 2,49,929 units day^{-1}
- Typical power exported to grid
  - During season = 318,892 units day^{-1}
    (13.29 MW day^{-1})
  - During off-season = 197,625 units day^{-1}
    (8.23 MW day^{-1})
- Typical No. of days of operation = 219 days (season)
  = 57 days off-season

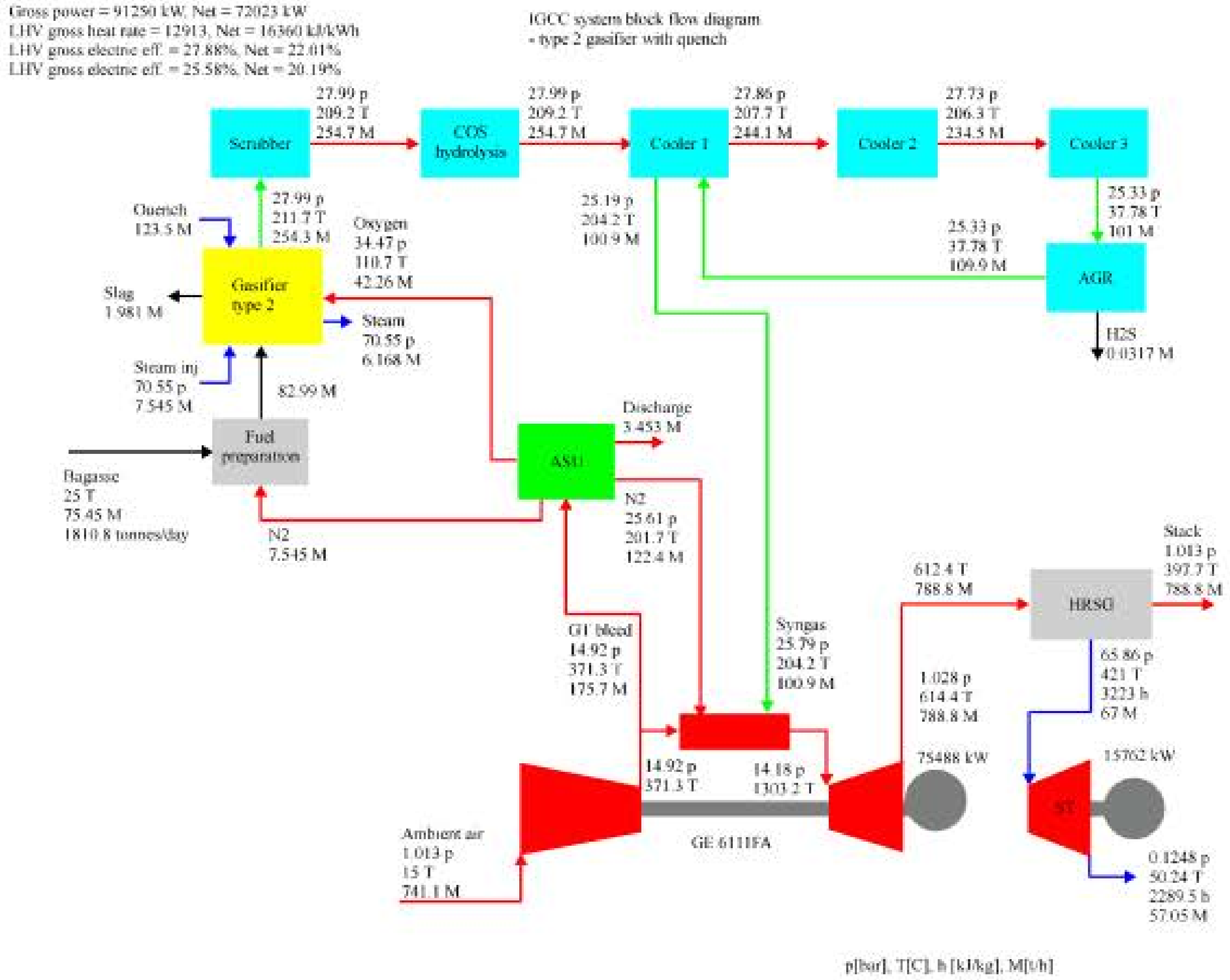

Fig. 6: Mass and energy flow chart (Off-season) for option 2

Option 2: Use of the BIG-CC

In this option, a BIG-CC plant (Fig. 2) including a gas turbine package equipped with a HRSG and a biomass gasifier and a 30 MW turbine should be installed in place of the old boilers and smaller steam turbine. By installing the BIG-CC plant in the sugar cane factory as option 2, instead of new boilers in option 1, Heat to the high capacity steam turbine is provided by the flue gas from the gas turbine to the Heat Recovery Steam Generator (HRSG). Note that the inlet steam condition to the new steam turbine in option 2 (65 bar/421°C) is similar to the conditions in option 1.

In this option, 1810 tonnes of biomass per day (in the season and off-season) or 660650 tonnes of biomass per year is needed. Thus, the shortfall of bagasse is a serious problem. However, by utilizing the surplus bagasse generated during the season, as well as by purchasing surplus bagasse, from other sugar mills and biomass fuels, such as, groundnut shell, paddy husk, cane trash and etc., the new co-generation plant can continuously be on the operation.

This option for the co-generation plant modification can enhance the power generation from 9 to 78.4 MW. Thus, surplus power of 69.4 MW is available for exporting to the grid. The new mass and energy flow charts for this option have been shown in Fig. 6 and 7.

The details of the BIG-CC and the steam distribution are as indicated below:

- **Gas turbine package:** 1 number of 77 MW
- **Gasifier:** 1 stage, oxygen-blown gasifier, the air source is gas turbine compressor and nitrogen is gas turbine combustor
- **Heat Recovery Steam Generator (HRSG):** 1 number of 150 TPH, 70 ATA
- **Steam turbines:** 1 number of 30 MW turbo-alternate (Extraction-cum-condensing type)
- **Mill drives:** 4 numbers of 900 HP DC motors, 2 numbers of 750 HP DC motors, 2 number of 1100 kW AC motors

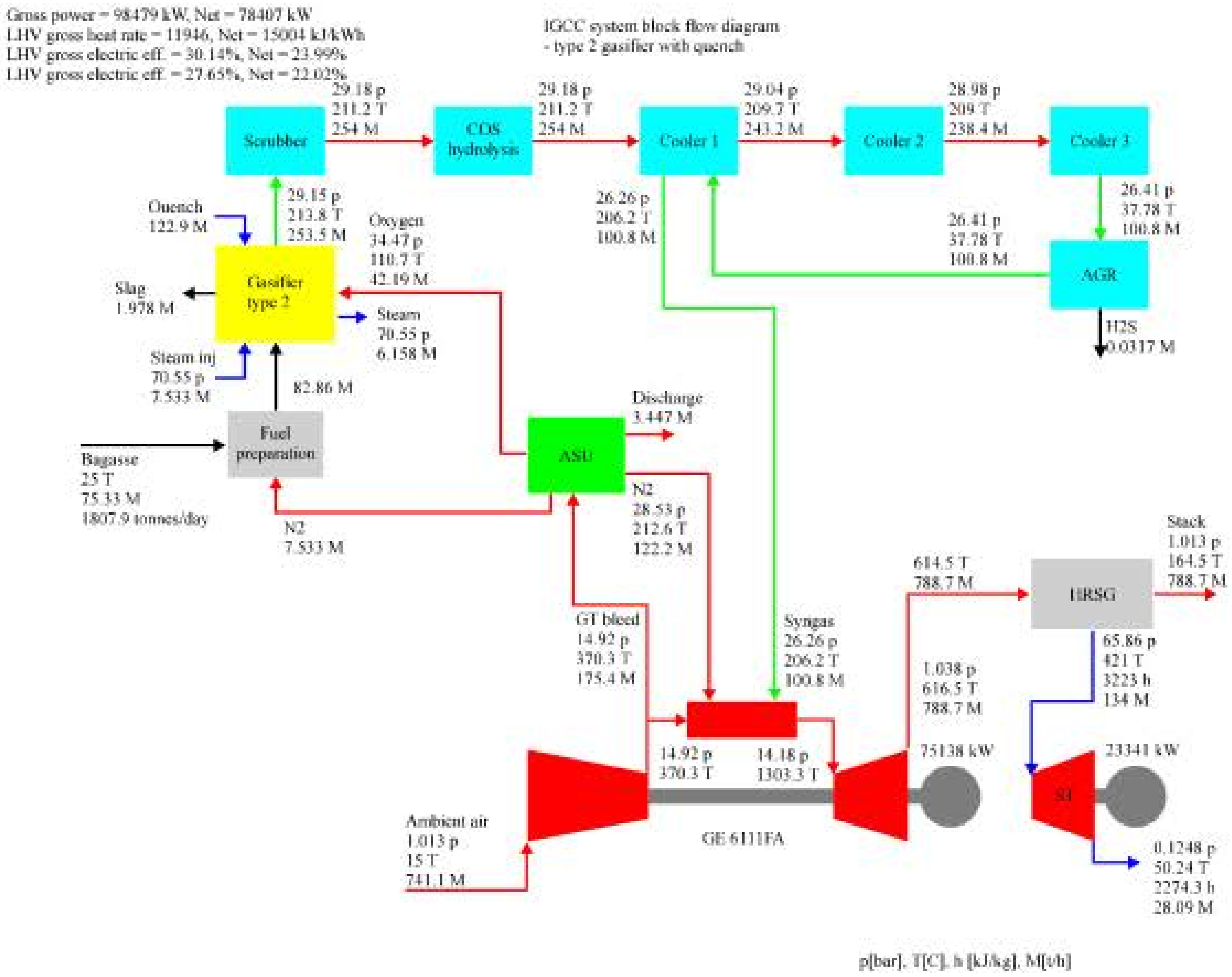

Fig. 7: Mass and energy flow chart (Season) for option 2

The implementation of the project will be completed in 36 months.
The following operating parameters can be achieved in option 2:

- Typical (average) crushing rate = 6000 TCD
- Typical power generation
  - During season = 1881768 units day^{-1}
  - During off-season = 1728552 units day^{-1}
- Typical power exported to grid
  - During season = 1641528 units day^{-1} (68.4 MW day^{-1})
  - During off-season = 1548072 units day^{-1} (64.5 MW day^{-1})
- Typical No. of days of operation = 219 days (season)
  = 57 days (off-season)

As shown, when a gasification plant, based on a general electric 5111FA gas turbine, is integrated with the typical mill, the net exported power will be 68.4 MW or more than 270 kW h/tonne cane.

Environmental Impact

In the evaluation of the atmospheric impact three main aspects were analyzed: (1) energy balance/CO_2 net emission; (2) methane and other greenhouse gases emissions and (3) particulate emission. By employing partial harvesting of non-burnt cane, the new technology (BIG-CC) will significantly reduce greenhouse gases and particulate emissions.

For example, in case of harvesting 3 million tonnes cane per year, a reduction in CO_2, methane, CO, NO_x, particulates of 0.15, 0.004, 0.09, 0.007, 0.0007 and 0.002 million tonnes or 0.52, 0.0117, 0.29, 0.023, 0.002 and 0.014 kg t^{-1} cane, respectively can be achieved. The main factors contributing to this reduction are the increased amount of biomass available for power production, the higher efficiencies in conversion and to a lesser extent, the avoided emissions as a result of less sugar cane burning.

CONCLUSIONS

One of the methods of increasing the co-generation power in a sugar mill is to replace the smaller low efficiency mill turbines, with better efficiency drives, such as, DC motors or hydraulic drives. This replacement can aid in increase of net saleable power to the grid, resulting in additional revenue for the sugar plant. In this case study, this replacement plan needs 1223900 USD and annual energy saving will be 825000 USD, so the simple payback period will be only 1.5 years.

The additional revenue for sugar industry by generating surplus power and supplying to national grid is possible. Whole of the fuel demand of a sugar cane factory with generation surplus power in its co-generation plant can be answered by produced bagasse as a bio-fuel.

The bagasse can be fired in the high pressure boiler for producing steam at high pressures, which is extracted through various back-pressure turbines and used in the process. Also, the high pressure steam can be produced in the HRSG which couples with the gasified bagasse burning gas turbine. This simultaneous generation of steam and power, commonly referred to as co-generation. In this study, some modifications of a commercial co-generation plant in a 6000 TCD mill were described.

These modifications contain minimization of process steam demand and high-pressure steam production, using high pressure boilers and condensing-extraction steam turbines and biomass integrated gasification. Annual monetary benefits achieved by modification of the co-generation plant in the case study (options 1 and 2) are 4 million USD (based on cost of power sold to the grid at 0.05$/kw h, sugar season of 219 days and off-season of 57 days) for option 1 and 22.4 million USD for option 2. The required investment for options 1 and 2 are 16 and 179 million USD, respectively. The investment had an attractive simple payback period of 4 years for option 1 and 8 years for option 2.

Because of the increased amount of agricultural residues available for power production, the higher efficiencies in conversion and to a lesser extent, the avoided emissions as a result of less sugar cane burning, the emissions of CO_2, greenhouse gases and particulates will be significantly reduced.

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