Techno-Economic Assessment of Biomass based Cogeneration Potential in KTDA managed tea factories

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Abstract— Kenya is a leading country in the production and trade of black CTC tea in the world. Every year the country produces in excess of 300 million kilograms of made tea with KTDA accounting for about 60% of this. But this production calls for huge supply of both thermal and electrical power to the tea factories to meet their process heat and electrical power demands. About 15% of total energy required in tea production is electrical while thermal accounts for 85%. Electrical power demand is mate primarily from the national grid while process heat is mate through own steam generation from combustion of biomass based fuels such as wood fuel, briquettes and also combustion of fuel oil in oil burning boilers/heaters. Operation of tea factories especially withering and drying, means there is always a constant demand for electrical and thermal energies in 1:6 ratio. This concurrent energy demand, mean that tea factories can install technically and economically feasible biomass based cogeneration units that expand steam through double stage turbine systems. The expansion of the steam results in quantifiable electrical power generation, while extraction of steam at lower pressures provides process steam for drying and withering process. Successful operation of Finlay's Saosa tea factory woodchip cogeneration plant in Kericho since 2009 shows that biomass cogeneration is a viable and feasible option for KTDA tea factories. Based on their current feedstock (biomass) consumption levels, the 58 KTDA tea factories have the potential to generate more than 30 MW electrical power and more than 264 MW of thermal power. Technologies like Combined Heat and Power systems (cogeneration) help in improving fuel use efficiency at the same time helping tea factories achieve their pollution control. This paper, presents a discussion on energy utilization in the tea factories, quantifies the cogeneration potential that is available in the tea factories based on current energy utilization and goes ahead to present possible lifetime cost of power generated.

Keywords- biomass, cogeneration, gasification, steam rankine cycle,

I. INTRODUCTION

A. *Study sample and methodology*

The study considered the entire population of 58 KTDA tea factories that were operational in 2009. For technical and economic assessment of cogeneration potential, three different cogeneration units 500 kWe, 600 kWe and 750 kWe based on steam system and biomass gasifier were considered. To understand energy consumption patterns of different factories, three of them-Kambaa, Rukuriri and Mogogosiek were selected based on their geographical location and crop production levels.

B. *Kenya Tea Sector at a glance*

Kenya is the largest producer of black CTC tea in Africa and the third largest in the world after China and India. The tea industry plays an important role in Kenya's economy and it's one of the success stories in Kenya's agricultural sector [1][2]. In the highlands West and East of the Rift-Valley endowed with adequate rainfall and low temperature, more than 158,000 hectares of arable land is devoted to tea cultivation [3].

Smallholder tea production accounts for 60% of tea production while privately owned large plantations accounts for the balance [1]. The small holder tea is processed and marketed by Kenya Tea Development Agency (KTDA) which manages tea processing factories on behalf of the farmers. In the plantation sector, James Finlay's (Kenya Ltd), Unilever Tea and Eastern Produce Kenya (EPK) Ltd are the major players [1][2].

C. *Tea production process*

The predominant tea processing method in Kenya is the cut tear and curl (CTC) method. A few factories such as KTDA Kangaita tea factory in Kirinyaga have Orthodox method alongside CTC to process orthodox tea. CTC method involves withering of freshly harvested green tea leaves that contains between 75–83% moisture on wet basis down to 65-66% moisture through trough withering process [4]. Fans located at the front end of the troughs are used to blow warm or cold air (depending on ambient condition at the time) through the tea leaves. Heat radiators mounted within the troughs assembly are used to warm the air whenever needed.

After withering, a rotor vane machine is used to shred/macerate the withered leaf. The macerated leaves are then passed through CTC Machine which cuts, tears and curl the preconditioned leaves. From the CTC, the finely cut leaves also known as the *'dhool'* is oxidized by subjecting it to warm/cold air blast depending on the season. It is the oxidation (fermentation) process that gives Kenyan tea its distinct flavor and aroma [4].

After oxidation, the tea is taken to fluidized bed tea dryers where the tea is subjected to a blast of hot fluidized air (of

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between 110 ^{0}C and 145 ^{0}C) reducing the moisture further down to 3%. Finally the processed tea is graded and packaged ready for market [4].

D. *KTDA Tea Factories Energy Demand and Utilization*

KTDA tea factories consumes approximately 0.13TWh of electricity, 413 thousand tones of wood fuel and 9.3 million liters of fuel oil or a combined total of approximately 1TWh of thermal energy [5]. KTDA tea factories get their electrical power primarily from Kenya Power and Lighting Company (KPLC) grid. Besides the national grid, the tea factories generates approximately 6.43GWh of own captive power using diesel generators [5]. In terms of electricity consumption, majority of the 58 tea factories considered in the study consumed between 1.5 and 3.0 GWh per annum with a few consuming less or more as figure 1 shows.

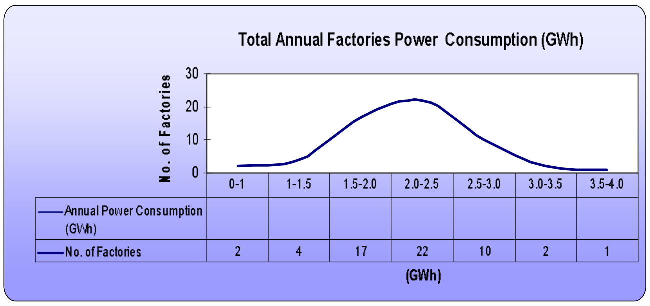


Fig. 1 Electrical Power Consumption

Since tea is a perennial plant, tea factories operate all year round with exception of few months per year when tea production is low due to adverse weather conditions. This means that there is almost a constant demand for thermal and electrical power all year round as figures 2 and 3 shows. The all year round demand for the two forms of energy is important for successful implementation of cogeneration in the tea factories.

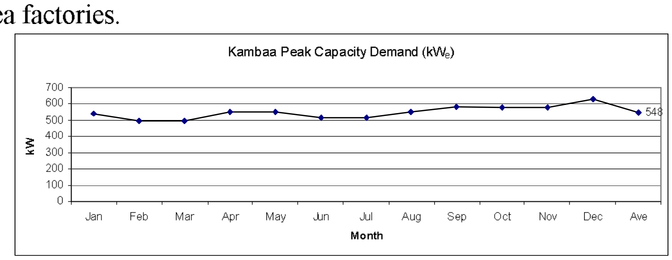


Fig.2 KTDA Kambaa T.F peak capacity demand

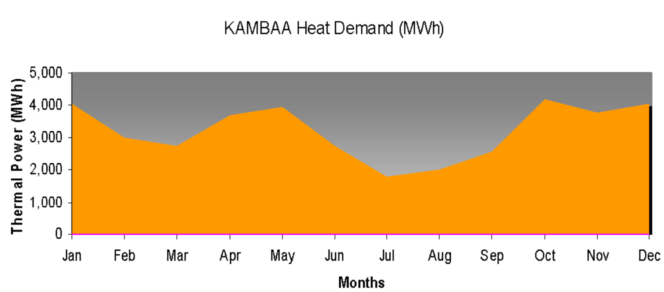


Fig.3 KTDA Kambaa T.F Thermal demand

KTDA Tea factory energy balance

Tea factories use both thermal and electrical energies for their operation. Thermal energy with steam as a carrier is used for withering and drying processes. The average specific thermal energy demand for KTDA tea factories is about 7.2 kWh kgMT [4]. A standard 44 troughs, 2 CTC lines tea factory requires about 9.2 tons of steam per hour. The thermal balance is such that, 53% of the process heat is for withering and 47% for tea drying as fig. 2 shows.

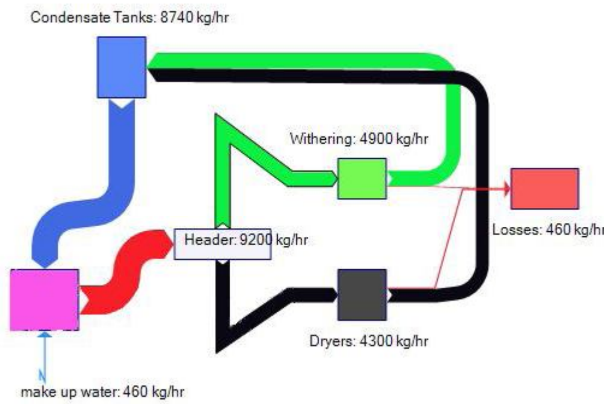


Fig. 4 Thermal (process heat) balance

II. COMBINED HEAT AND POWER PRODUCTION (COGENERATION)

Co-generation or Combined Heat and Power (CHP), is defined as the simultaneous (or shared) production in the same facility of two different forms of useful energy-electric and mechanical power plus useful thermal energy from a single primary energy source and same technological [6][7][8].

The electrical energy produced, can be utilized on site (captive use), exported to the grid or both if the system is grid-synchronized. The thermal energy can be used either for direct process application or indirectly for producing steam, hot water, and hot air for dryer or chilled water for process cooling [6][7][9].

The principal advantage of cogeneration over other power generation technologies is that, the amount of fuel needed to produce both heat and power, is much less than total fuel needed to produce electricity and thermal energy through separate technologies [6]. The overall efficiency of energy use in co-generation mode can be as high as 85% or higher depending on the plant use [6].

Co-generation units utilize a variety of fuels that includes solid and gaseous biomasses, gas, coal, light fuel oils, waste fuels and energies from industrial processes [9][10]. Most biomass fueled co-generation units are steam rankine cycle (SRC) processes using fluidized bed boilers/grate furnaces [9].

Since small scale biomass co-generation units are located closer to the load center than central power plants, effective total emission will be reduced due to elimination or reduction in transmission and distribution (T&D) losses as well as T&D costs which constitutes over 30% of total electricity costs [11][12].

Economically, Combined Heat and Power (CHP) make sense from both macro and micro perspectives. At the macro level, co-generation units which forms part of a distributed generation (DG) network accords national electric utility companies an alternative to expensive systems capacity upgrade since the burden is shared with the private sector [12][13]. Besides costs deferral, co-generation under DG offers opportunity for indigenous energy sources to be conserved.

III. TECHNICAL OPTIONS FOR BIOMASS COGENERATION IN KTDA TEA FACTORIES

There are many cogenerations options that can be applied by KTDA tea factories. But this paper presents two of these options based on their technical and economic suitability from the factories standpoint. The two are steam turbine system and biomass gasification.

A. *Steam Turbine System*

Steam turbine represent one of the most versatile and oldest (>100 years) prime mover technologies in general use [14]. They are preferred due to their higher power efficiencies and lower investments cost. Its major drawback is inertia. The system does not work well where is there is intermittent need for energy especially thermal. But this is not a major problem to the use of steam turbine system in the tea factories since there is almost a constant thermal load throughout the year.

Common thermodynamic cycle for steam turbine in power generation is the rankine cycle [14]. Commonly used systems are back pressure, and extraction-condensing systems. The extraction-condensing is the most suitable system for tea factories and most process industry since it allows extraction of steam at different pressures and temperatures. Since steam turbine systems run on many fuels such as biomass and fuel oil, there is adequate feedstock in the factories to support such as system.

B. *Biomass Gasification*

Gasification involves the conversion of carbonaceous solids in biomass into a combustible gas by controlling or limiting the rate of oxygen (air) admitted to the fuel bed [15]. Gasification process involves pyrolysis and thermal cracking under partial oxidation at temperatures ranging from 700 ^{0}C to 1000 ^{0}C the gaseous product thus obtained is known as producer gas (syngas) and constitute mainly combustibles such as hydrogen, methane, carbon monoxide and non-combustibles such as carbon monoxide, water vapour and nitrogen [16].

Biomass gasification as a cogeneration option is only possible in a Gasifier-Internal combustion Engine (ICE) hybrid system. In this system, the syngas produced is combusted in a water jacketed IC engine. The water used to cool the IC engine is heated and used to provide low grade process heat for withering process. The mechanical power from the engine is used to run a power generator which produces electricity to power the factory machinery.

C. *Factors Influencing Cogeneration type to adopt*

Selection of a particular co-generation technology or operating scheme is dependent on energy consumption profile of the particular site in this case, the tea factories. Ideally, a cogeneration unit can be designed to match the base electrical load of the factory, the base thermal load, or the total electrical/ thermal load.

Based on KTDA tea factories operations, the cogeneration units are best designed to meet the total thermal load of the factory. This is informed by the fact that, unlike electrical load that can be part mate by own cogenerated power with the deficit being drawn from the national grid, the factories have to meet 100% of their thermal load since there are no external sources to the factories to meet the same.

In the thermal matching, the factory cogeneration unit meets the entire site thermal requirements independent of auxiliary thermal generation all year round. The electrical system is grid synchronized, such that, any deficit is mate by purchase from the grid while surplus is sold to the grid.

D. *Steam rankine cycle*

Small scale biomass fueled co-generation units generating less than 20 MWel are based on steam Rankine cycle (SRC) with steam superheating [9]. This is a form of closed thermal cycle power generation since fuel (biomass) is combusted in a furnace, producing hot flue gases which are used to generate steam for power production.

In SRC, the steam from the boiler is superheated at constant pressure raising its temperature above its saturation point. For a power only steam condensation turbine system, cooling water in a heat exchanger is used to condense the steam to water after it has expanded through the turbine with expansion being limited by the moisture content of the steam after the turbine which typically has maximum moisture content of about 12% [Ibid].

For industrial application where thermal energy is needed at higher temperature and pressure, the steam is extracted from the turbine at the required pressure and temperature with remaining steam expanding to condensation state. This configuration is known as back-pressure turbine system. But the higher pressure and temperature after back-pressure turbine reduces power production of the co-generation unit [Ibid].

IV. RESULTS: TECHNICAL ASSESSMENT OF BIOMASS CO-GENERATION

Using data from technical and economic assessments it was possible to quantify how much co-generation potential exists in KTDA managed tea factories and by inference in the whole of Kenya's tea sector.
These three approaches were used:

- **Reference case:** *Current electrical power and process heat demand of the factories and energy balances as presented in sections 4.8*
- **Alternative Scenario 1**: *Best Technical option: using a 750 kW$_{el}$, 43 bar (abs) 10 tons per hour back-pressure steam turbines system with single extraction or use of a 750 kW$_e$ Biomass gasifier with I.C engine*
- **Alternative Scenario 2:** *based on current biomass consumption in KTDA factories*

Reference case: Current Electricity and Heat Demand

Every kilo of made tea requires between 3.5-6 kWh$_{th}$ of thermal energy, 0.21 to 0.5 kWh$_e$ of electrical energy and 0.11 kWh of manpower [17]. In 2008 (reference year), KTDA tea factories thermal energy intensity averaged 4.72 kWh$_{th}$ KgMt^{-1} while the electrical power intensity averaged 0.62 kWh$_e$ KgMt^{-1}. From the upper limits of thermal and electrical power intensities (6.0 kWh$_{th}$ KgMt^{-1} and 0.5 kWh$_e$KgMt^{-1}, and average 210 million kilograms of made tea production, co-generation potential based on the above parameters would be 21 MW$_e$ of electrical power and 252 MW$_{th}$ of process heat energy per annum (5000 hryr^{-1}). Considering total electricity and heat consumption in the 58 KTDA tea factories considered in the study, the available co-generation potential is approximately 26 MW$_e$ of electricity and 200 MW$_{th}$ of thermal energy.

Alternative Scenario I: Best Technical Option (installation of a 750 kW Cogeneration Unit)

Even though the study considered three different cogeneration units: 500 kWe, 600 kWe and 750 kWe that can be installed in the tea factories, technical and economic analysis of the three units showed that a 750 kW$_e$ SRC unit is most viable technically and economically for the tea factories. Using a steam turbine rated at 43 bar (abs) in-let pressure and 10 tons/hr steam flow rate and assuming 70% load factor, technical co-generation potential of the 58 factories considered in the reference case would be 30 MW$_e$ of electrical power and 361 MW$_{th}$ of thermal power. Alternatively, using a 750 kW$_e$ rated biomass gasifier with the producer gas being combusted in an Internal Combustion (IC) engine for electricity production and assuming 80% load factor and a heat to power ratio of 0.78 [18][19], the available co-generation potential would be 35MW$_e$ of electrical power and 27 MW$_{th}$ of thermal power from the 58 KTDA factories.

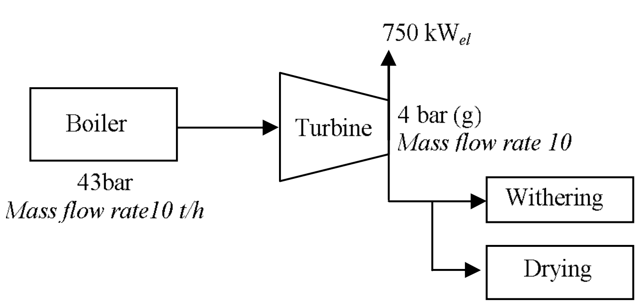


Fig.5 Typical layout of a 750 kWe steam turbine cogeneration system

Alternative Scenario II: Current Biomass Consumption

On average, KTDA tea factories consume approximately 413 thousand metric tons of fuel wood. Taking a lower heating value (LHV) of woody biomass to be 14.4 MJ kg^{-1}, the thermal energy from this consumption is 5.95 PJ. A co-generation unit rated 750 kW$_e$ using steam cycle process needs approximately 0.16 PJ of biomass energy per year in CHP mode. Therefore, based on biomass consumption levels, there is potential to generate approximately 20 MW$_e$ of electricity and 232 MW$_{th}$ at 70% conversion efficiency.

V. RESULTS: ECONOMIC ASSESSMENT OF BIOMASS CO-GENERATION

The main basis for economic assessment was the lifetime cost of generation (LCG)/cost of electricity (COE) of the different cogeneration options available. Three different lifetime costs of generation (LCG) were derived. LCG I considered the useful output from the cogeneration plant to be electrical power alone. LCGII considered both power and heat (CHP) as useful outputs, while LCG III considered electrical power, heat and net CDM effect as outputs.

The economic assessment presented in this section, considers different economic parameters of three different cogeneration units options: 500 kWe, 600 kWe and 750 kWe that can be installed in KTDA tea factories based on their current energy utilization levels. Table 1 shows specifications of power costs of steam turbine cogeneration units while table 2 shows the power costs of biomass Gasifier-Internal Combustion Engine cogeneration units. In both cases, 750 kWe units had the best parameters in terms of total specific investment costs, specific annual operations and maintenance costs and efficiency of fuel to net power. The biomass gasifier system has better system parameters than turbine system especially on total specific investment costs and efficiency of fuel to net power. This is due to the fact that, there is no steam generation involved and the process heat derived from the system is a byproduct of the gasifier cooling system.

Table 1Steam turbine system

Steam Turbine System Cogeneration Unit				
Specifications of power Costs		Option I	Option II	Option III
Plant gross power capacity	*kW$_e$*	***500***	***600***	***750***
Plant net power capacity (Average)	*kW$_e$*	*350*	*420*	*525*
Total specific investment cost	*US$ kW$_e^{-1}$*	*2,333*	*2,350*	*2,092*
Specific equipment costs	*US$ kWe^{-1}*	*1,980*	*2,056*	*1,912*
Specific civil works costs	*US$ kW$_e^{-1}$*	*353*	*294*	*235*
Specific annual O&M costs	*US$ year^{-1} kW$_e^{-1}$*	*60*	*58*	*50*
Equivalent full power load operating hrs per year	*hrs year^{-1}*	*5,000*	*5,000*	*5,000*
Economic Lifetime	*years*	*15*	*15*	*15*
Efficiency fuel to net power (Annual average)	*kWe*	*5.6%*	*6.7%*	*8.4%*

Table 2 Biomass gasifier system

Biomass Gasifier with ICE Cogeneration Unit				
Specifications of power Costs		Option I	Option II	Option III
Plant gross power capacity	kW_e	***500***	***600***	***750***
Plant net power capacity (Average)	kW_e	*350*	*420*	*525*
Total specific investment cost	*US$* kW_e^{-1}	*1,487*	*1,378*	*1,270*
Specific equipment costs	*US$* kWe^{-1}	*1,150*	*1,096*	*1,045*
Specific civil works costs	*US$* kW_e^{-1}	*353*	*294*	*235*
Specific annual O&M costs	*US$* $year^{-1}$ kW_e^{-1}	*69*	*57*	*46*
Equivalent full power load operating hrs per year	*hrs* $year^{-1}$	*5,000*	*5,000*	*5,000*
Economic Lifetime	*years*	*15*	*15*	*15*
Efficiency fuel to net power (Annual average)	kW_e	*19%*	*19%*	*19%*

Table xx shows a comparison of carbon emissions reductions from both steam turbine system and biomass gasifier. Factories currently using high amount of fuel oil, stand to gain the most from carbon trading, since to them installation of biomass cogeneration units will be accompanied by fuel substitution (fuel oil to biomass).

Table 3 Carbon emissions reductions

Carbon Emissions Reductions				
Parameters	**kWe**	**500**	**600**	**750**
Total fuel cost (Transport and cost)	*US$ton*$^{-1}$	*9*	*9*	*9*
Total plant CO_2 emissions	*tons* CO_2	*0*	*0*	*0*
Grid baseline emissions CO_2 per unit power	*kg* CO_2 kWh^{-1}	*0.6*	*0.6*	*0.6*
Avoided grid CO_2 emissions	*tons* CO_2	*1,500*	*1,800*	*2,250*
Avoided CO_2 emissions from fuel oil combustion	*tons* CO_2	*3,209*	*0*	*31,273*
Avoided CO_2 emissions from Diesel combustion	*tons* CO_2	*66*	*76*	*76*
Net plant reduction in CO_2 emissions	*tons* CO_2	*4,775*	*1,876*	*33,599*
Estimated CER price	*US$ CER*$^{-1}$	*10*	*10*	*10*
Net CDM effect (Averaged over plant economic lifetime)	*US$* kWh_e^{-1}	*0.010*	*0.003*	*0.045*

Table xx shows different lifetime cost of power generation from for the three different cogenerations units as steam turbine systems and biomass gasifier-ICE systems. From the table, both steam turbine system and biomass gasifier systems have the same LCG II (considering power and heat outputs) at 0.03 US$/kWh. When one factors in the CDM effect, the cost of electricity for a 750 kWe unit falls below zero effectively meaning that the units earns US$ 0.09 kWh^{-1} and US$ 0.02 kWh^{-1} respectively. But this is only applicable to factories with high consumption of fuel oil for steam generation. CDM effect is negligible for factories with low or no fuel oil consumption.

Table 4 Economic parameters

Parameter		**Steam Turbine Syst.**			**Gasifier-ICE System**		
	kWe	**500**	**600**	**750**	**500**	**600**	**750**
IRR	%	17%	21 %	51%	69%	111%	147%
PB	years	3.8	3.8	2.8	2.6	1.9	1.6
LCGI	US$/kWh	0.12	0.14	0.12	0.06	0.06	0.05
LCGII	US$/kWh	0.07	0.05	0.03	0.03	0.04	0.03
LCGIII	US$/kWh	-0.07	0.04	-0.09	-0.03	0.03	-0.02

To analyze the impact of uncertainty associated with the input data and the assumptions used for economic assessment of the options, a sensitivity analysis was performed. The relative simplicity in the main economic indicator model called for a sensitivity check. LCGII was chosen for analysis since it incorporates the principle of cogeneration (heat and power production) as reference case.

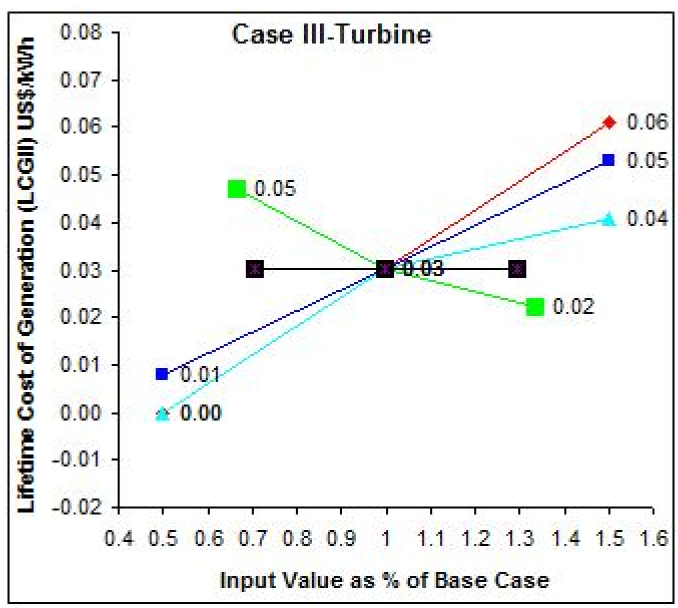
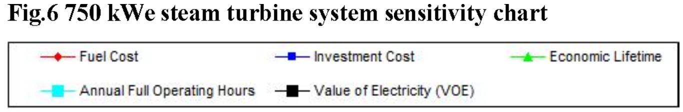


Fig.6 750 kWe steam turbine system sensitivity chart



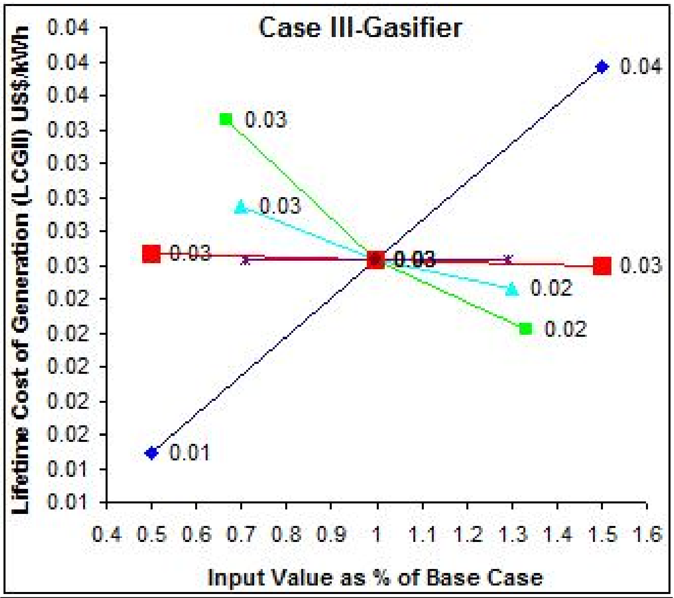


Figure 7 750 kWe gasifier system sensitivity chart

VI. Conclusion

There is technically and economically viable potential for biomass cogeneration in KTDA tea factories. The most viable system to be installed in the tea factories is a 750 kWe steam turbine cogeneration system. Such a system would be able to generate enough electricity to power the factory machinery and also provide enough process heat for tea production but implementation of the same requires steam generation equipments upgrade.

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