Technoeconomic Analysis of an Integrated Gasification Combined Cycle System as a way to utilise Bagasse

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Abstract- Sugar cane milling processes leave a waste solid residue, known as bagasse, which is subsequently combusted with the aim of covering the energy demands of the sugar plants. An alternative way to co-generate electricity and heat is via the integrated gasification combined cycle (IGCC) process. The main sections of this process are the gasification unit and the combined power generation cycle (Brayton-Rankine) and it is usually preferred to combustion in small scale applications due to enhanced electricity yields and lower emissions. Therefore, the aim of this study is to examine whether or not the IGCC process is more feasible than combustion for the utilisation of bagasse (large scale application). Aspen plus process simulator was employed to simulate the investigated system and based on the simulations technical and economic analyses were carried out. Consequently, the cost of electricity was calculated and compared with that derived from combustion systems. So far, to the best of our knowledge, no comparative assessment between the basic biomass-to-electricity processes was attempted. Thus, the present study focuses on integrating exhaustive process simulations along with thorough energetic and financial calculations to evaluate the feasibility of the IGCC process. This methodology provides a robust mechanism and can be used as a reliable decision making tool.

Keywords Power plant technoeconomics, IGCC, Cost of electricity from biomass, Bagasse utilisation.

1. Introduction

The fluctuations in price, as well as the increases in greenhouse gas emissions (GHG) have motivated researchers to explore alternative sources of energy that have the potential to provide sustainability. The refocusing of the global energy economy towards a greener pathway will, however, not be an easy task, at least not until the utilization of renewable raw materials is commonplace. To achieve this, a successful alternative energy source should meet the following feasibility criteria **[1]**: 1) It should be readily available, 2) it should be cheap, 3) it should be GHG neutral and 4) it should not offer a threat to food and land availability. In view of these, sugarcane bagasse can be considered as a potential feedstock for a sustainable bioenergy sector. Bagasse is a solid lignocellulosic residue of the sugar cane milling processes for ethanol or sugar production; 1 tonne of sugar cane leaves approximately 250 kg of bagasse **[2]**. In most cases this bagasse is misused to low pressure boilers to cover the electricity demand of the sugar plants. Therefore, its exploitation, in a more effective manner, would increase electricity yields and provide a significant solution to overcome waste problems. Moreover, as a waste material, it will be considerably less expensive than other biomass material such as wood **[3]**. Another advantage is that there is no competition with the accessibility and usage of food and land. Essentially, it prevents the tightness of food supply and averts the conflict with the cultivation of farmland **[4]**. Similarly to various energy crops, it manages neutral carbon footprint.

Gasification is a similar process to combustion but with different operating conditions (lower air:biomass ratio and temperature). The main goal is to produce syngas (a mixture of carbon dioxide and hydrogen) which subsequently is subjected to various treatments in order to give a wide range of products **[5]**. As oxidant, air, purified oxygen, steam or even a mixture of these could be utilized. Air gasification generates a producer gas with energy content of 3-5 MJ m^{-3} (STP) which contains a large amount of nitrogen (approximately 50% v/v). This results in a more intensive downstream process, reducing the overall economic and thermodynamic efficiency of the plant. The lower heating value of the producer gas can be increased to 9-13 MJ m^{-3} (STP) if oxygen is used as medium. Nevertheless the requirement for an air separation unit affects negatively the investment cost. In theory steam gasification can augment the syngas energy content to around 13-18 MJ m^{-3} (STP) mainly because of the increased yields of methane and lower hydrocarbons **[6]**. Following gasification the gas must be cooled down so as to be separated from the water, treated to remove the tar content and then subjected to purification with the aim of withdrawing CO_2 and additional pollutants such as H_2S. Then, the cleaned syngas enters the gas turbine unit where it is burnt with excess of air to produce electricity. Finally, the heat content of the flue gas is recovered in a series of heat exchangers where high quality steam is raised which subsequently drives a steam turbine unit **[7]**. **Figure 1** is a simplified schematic of the IGCC process.

The scope of this study was to perform feasibility analysis on generating electricity from bagasse via gasification. For this purpose, exhaustive process simulations and thorough economic calculations were conducted with the aim of comparing the cost of electricity with that obtained from conventional combustion systems.

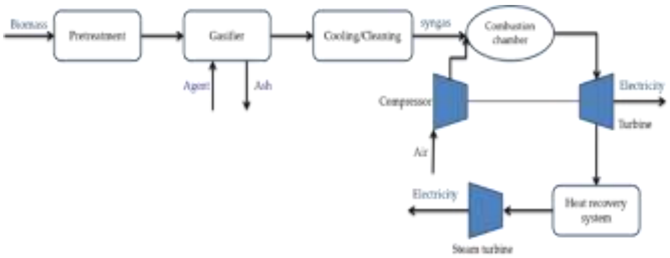

Fig. 1. Simplified schematic of the IGCC process

2. Process Simulation

An Aspen plus model has been developed in order to simulate the gasification of sugarcane bagasse. The inlet mass flow rate was set equal to 100 t h^{-1}. User defined non-conventional solids were determined to symbolize bagasse and ash. Aimed at those modules two Aspen models were allocated: one for the density (DCOALIGT) and the second one enthalpy (HCOALGEN) that necessitates awareness of proximate analysis and ultimate analysis of the bagasse **[8]** (see **Table 1**). Finally tar formation has been taken into account and simulated as toluene. The physical properties of the conventional components have been estimated by using the Redlich-Kwong-Soave cubic equation of state with Boston-Mathias alpha function (RKS-BM). This method is suitable for gas-processing, refinery and power generation applications such as gas plants, crude towers and gas turbines. Using the RKS-BM model, rational and reliable outcomes can be anticipated at all temperatures and pressures **[9]**. The SOLIDS property option was employed for the biomass crushing and drying units as it is recommended for solids processing unit operations. The Aspen plus model for the IGCC process can be divided into four sections: 1) Bagasse pretreatment, 2) gasification of bagasse, 3) syngas conditioning and 4) power and heat generation unit. the biomass crushing and drying units as it is recommended for solids processing unit operations. The Aspen plus model for the IGCC process can be divided into four sections: 1) Bagasse pretreatment, 2) gasification of bagasse, 3) syngas conditioning and 4) power and heat generation unit.

Table 1. Typical bagasse Proximate and Ultimate analysis**[8]**

Proximate analysis	
Parameters	**Mass**
Moisture	50 (wb)
Ash	3.2 (db)
Volatile matter (dry Basis)	83.65 (db)
Fixed Carbon (dry basis)	13.15 (db)
Ultimate analysis	
Element	**Dry**
C	45.38
H	5.96
O	45.21
N	0.15
S	0.1
Energy Content	
HHV = 19 MJ kg^{-1}	
LHV = 17 MJ kg^{-1}	

2.1. Pretreatment unit

A standard Aspen plus block for a crusher was employed to simulate a gyratory crusher which chops bagasse to a final particle size equal to 2 mm **[10]**. A gyratory crusher was selected due to its low power requirement, robust construction and low operating costs. After this, bagasse enters a dryer in order to reduce its moisture content to 10 %. For this purpose a fluidised bed dryer was used since the high rate of heat and mass transfer accomplished guarantees much faster and more homogeneous drying than attained by using other techniques such as oven and vacuum drying **[11]**. The high initial moisture content of bagasse makes it necessary to employ a dryer so as to reduce heat losses in the combustor unit. The fractional conversion of bagasse to water was estimated by embedding a FORTRAN statement into the main model. The energy required for the drying process is provided by the flue gas exiting the power generation unit. After the dryer a common separator block was used to remove the moisture.

2.2. Gasification unit

For simulation purposes, prior to the gasification unit, a RYIELD reactor was employed to decompose bagasse to its constituent elements by using a FORTRAN statement based on the ultimate analysis. Then the producer stream enters the gasification unit. A steam fluidised bed gasifier was considered operating at atmospheric pressure. The RGIBBS reactor module was employed to simulate the gasifier which assumes an overall equilibrium and neglects the hydrodynamic and kinetic features of the reactor. This approach has been used before in several studies **[12, 13]** and it is suitable for feasibility studies but not for reactor design **[14]**. **Table 2** presents the participant gasification reactions and it was assumed that they have reached reach chemical equilibrium.

Table 2. Typical Steam Gasification Reactions **[15]**

Reactions (1-8)	**ΔH$_r$, Heat of reaction (kJ mol^{-1})**
$C + 2H_2 \leftrightarrow CH_4$	-32.62
$C + H_2O \leftrightarrow CO + H_2$	+124.97
$C + CO_2 \leftrightarrow 2CO$	+187.67
$CH_4 + H_2O \leftrightarrow CO + 3H_2$	+157.22
$CO + H_2O \leftrightarrow CO_2 + H_2$	-63.98
$N_2 + 3H_2 \leftrightarrow 2NH_3$	-92
$H_2 + S \leftrightarrow H_2S$	-20
$C_7H_8(Tar) + H_2O \leftrightarrow 7CO + 11H_2$	+469.17

In general, the predictions of the model were in good agreement with published experimental data **[16]** (as depicted in **Figure 2**). Furthermore, in this study as design variable for the gasification process the lower heating value (LHV) of the producer gas was selected. This can be calculated by utilising the following equation:

$$LHV_{syn} = 239.92 \times MoleFlowRate_{H2} + 281.54 \times MoleFlowRate_{CO} + 802.34 \times MoleFlowRate_{CH4} \quad (1)$$

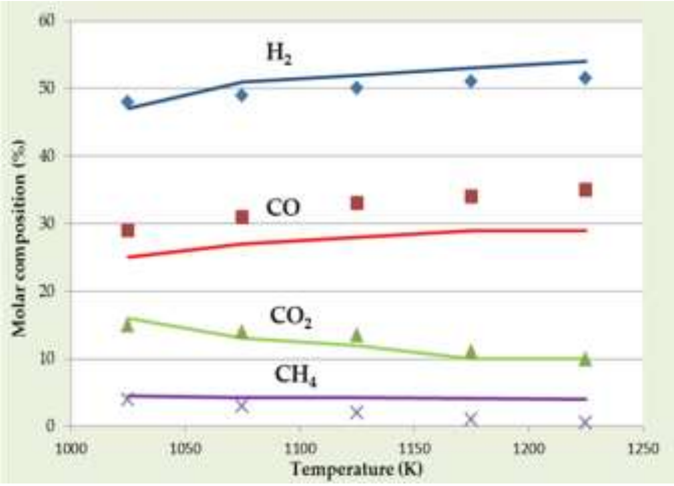

Fig. 2. Comparison of model prediction with experimental data **[16]** for bagasse gasification

The goal is to identify the conditions that maximize the LHV of the producer gas since the higher the LHV the higher the power output of the gas turbine. These conditions are temperature of 1000K and steam to biomass ratio of 1. The LHV of the producer gas is maximised for a steam to biomass ratio of 1. Further introduction of steam results in methane decomposition and consequently the overall energy content of the producer gas is decreased whereas further increase in temperature favours the production of CO_2 over CO. This effect has been reported in previous similar studies **[17]**. After the gasifier, two cyclones were used, the first one separates the unreacted char from the producer gas and recycles it to the gasifier and the second distinguishes the ash from the gas mixture.

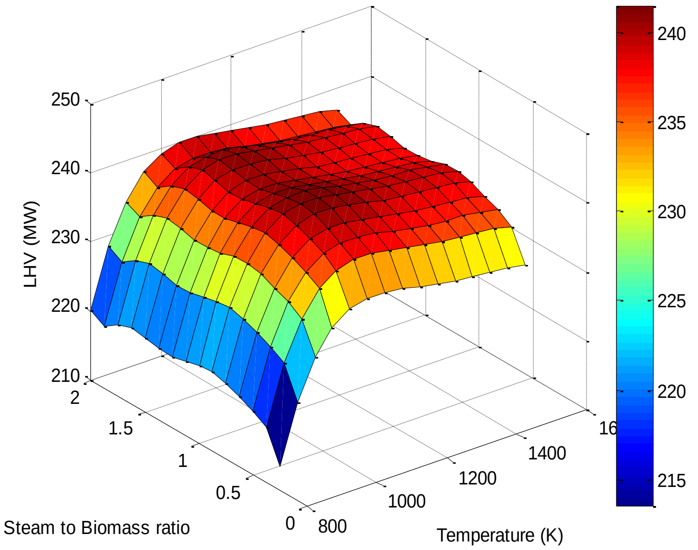

Fig. 3. LHV versus Temperature and Steam to biomass ratio for bagasse gasification

2.3. Syngas conditioning

The next step is to purify the producer gas, thus an RSTOICH reactor has been employed to simulate a catalytic reformer reactor with the intention of removing the tar (simulated as toluene). An Ilmenite based catalyst was used because it promotes mainly tar reforming over methane which is desired due to its high heating value. The next step is to remove ammonia, thus an RSTOICH reactor (efficiency of 100% was assumed) has been employed to simulate an ammonia scrubber where ammonia is removed using water and sulphuric acid. Ammonia reacts with the sulphuric acid to form ammonium sulphate. Subsequently, the acid gases H_2S and CO_2 are removed by using a solution of monoethanolamine (MEA) in an absorber. Amines are in general weak bases and because of that they are preferable to a strong base (e.g. NaOH) since they can be easily separated from the acid gases (by employing a stripper) and eventually recycled to the absorber. Finally, the producer gas is cooled down to produce steam that enters the gasifier and a flash drum was employed to separate liquids (water, ammonium sulphate) from the gas mixture.

2.4. Power generation unit

The purified syngas is then compressed up to 6 bars and enters a gas turbine where it is burned with excess of pressurised air (Air equivalence ratio=1.5) to produce electricity at temperature of 1800K, conditions at which the gas turbine power is maximised (see **Figure 4**). The required air is specified by a FORTRAN calculator according to the flows of methane, carbon monoxide and hydrogen. Syngas is pressurized in a two stage intercooling compressor while the combustor has been simulated as a plug flow reactor at steady state. The reactions occurring in the combustor as well as their kinetics are as follows **[18]**:

$$H_2 + O_2 \rightarrow H_2O,\ \ R_1 = 1 \times 10^{11}\exp(\frac{-5051}{T}) \tag{2}$$

$$CO + 0.5O_2 \rightarrow CO_2,\ \ R_2 = 1 \times 10^{12}\exp(\frac{-15996}{T}) \tag{3}$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O,\ \ R_3 = 2.6 \times 10^{12}\exp(\frac{-15623}{T}) \tag{4}$$

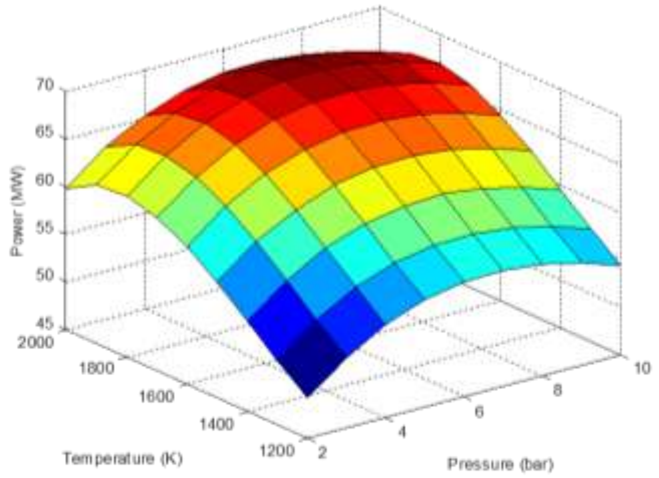

Fig. 4. Sensitivities on gas turbine power for the IGCC system

The exhaust gas from the gas turbine is recovered from a heat recovery steam generation (HRSG) system, composed of three heat exchangers (namely economizer, evaporator and superheater) where high value steam is produced, and eventually electricity, is generated in a steam turbine. **Table 3** illustrates the technical data of the IGCC process.

3. Results

3.1. Energy efficiency

Given the process technology modelled and integrated the energy efficiency of the IGCC system can be calculated by utilising **Eq. (5)**. The energy, η, efficiency is defined as the ratio of the generated electricity to the energy contained in the feedstock. Hence, the IGCC process attains a value of 45% which is rather higher than the efficiencies of biomass combustion systems (30%-38%) that have been reported in the literature **[19-21]**.

$$\eta = \frac{W_{out}}{\dot{m}_{bagasse} LHV_{bagasse}} \tag{5}$$

Where W_{out} refers to power generated throughout the process and $\dot{m}_{bagasse}$ is the bagasse mass flow rate on a dry basis.

Table 3. Technical data for the IGCC system used in the present study

Compressor isentropic efficiency (%)	92
Compressor mechanical efficiency (%)	88
Turbine isentropic efficiency (%)	93
Turbine mechanical efficiency (%)	90
Gas turbine power (MW)	67
Steam turbine power (MW)	45
Steam temperature (K)	773
Steam pressure (bar)	80

3.2. Energy losses

Energy analysis can be used to compare components or systems to help make informed design decisions. By analysing the energy destroyed within a process, it is possible to identify the stages that need to be improved. **Figure 5** depicts the energy losses per section for the IGCC process. The overall losses are equal to 136 MW. It can be observed that the major contributor to the losses is the gasifier (30%), followed by the gas turbine and of the lowest significance is the drying unit.

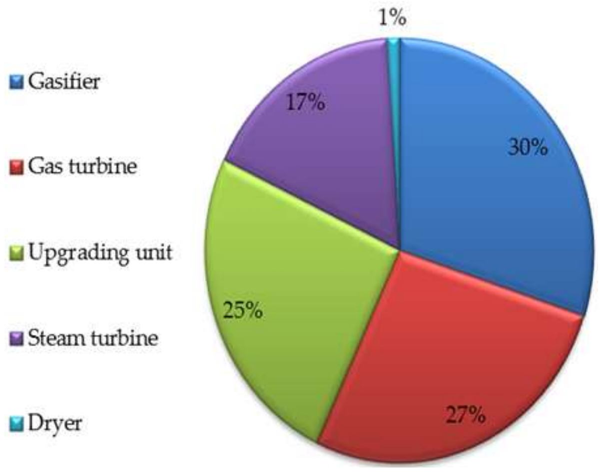

Fig. 5. Energy losses per section for the IGCC process

3.3. Energy costing

Energy analysis has been finalised by calculating the cost related to the energy destruction throughout the process. This expenditure (C_E) refers to the cost of producing a fuel which can provide useful energy equal to the destroyed energy under the same conditions. It can be described by **Eq. (6) [22, 23]**. It is quite obvious that there is a strong connection between efficiency and cost – the greater the efficiency the lower the energetic costs.

$$C_E = \frac{I \times h \times q}{\eta} \tag{6}$$

Where I is the amount of the energy losses, h is the annual working hours of the plant, q the bagasse cost (= 10 \$ t^{-1} or 0.611 \$ GJ^{-1}) and η the energetic efficiency. Thus, due to energy losses an economic loss of approximately M\$ 4.3 per annum was calculated.

3.4. Economic evaluation

3.4.1. Equipment costing

The estimation of the equipment cost was carried out by utilizing **Eq. (7)** and it is based on historic data that can be found in the literature **[24]**.

$$C = C_0\left(\frac{S}{S_0}\right)^f \tag{7}$$

Where C is the estimated actual cost of the unit, C_0 the base cost of the unit, S the actual size or capacity of the unit (derived from the simulations), S_0 the base or capacity and f an empirical scaling factor. The values of C_0, S_0 and f are summarised in **Table 4**.

3.4.2. Capital and operating costs

After the estimation of the equipment cost, it is possible to proceed in calculating the direct and indirect costs of the process by following the methodology proposed by Peters *et al*. **[27]**. According to this method the direct and indirect costs are calculated as a percentage of the equipment cost (EC), as illustrated in **Table 5**. The total capital investment (TCI) derives from the summation of direct, indirect and equipment costs. Finally, the operating costs (OC) mainly comprise feedstock, utilities and labour expenditures and are presented in **Table 5**.

3.4.3. Cost of electricity

The outcomes of the economic assessment are depicted in Table 6 and compared with the respective costs for combustion systems. A significant feasibility index for power generation technologies is the calculation of the electricity cost (see **Eq. 8**). It is a significant index especially

Table 4. Equipment cost correlation factors **[25, 26]**

Equipment	Cost Equation		
	S_0	f	C_0 (M\$)
Gasifier	69 dry t/h	0.7	15
Syngas Cooler	77 MW_{th}	0.65	25.4
Gas Turbine	266 MW_e	0.7	56
HRSG + heat exchangers	355 MW_{th}	1	41.2
Tar Reformer	100 t h^{-1}	0.65	3.8
Syngas Compressor	10 MW_e	0.67	4.83
Feedstock handling and drying	500[a]	0.7	6.2
Quenching unit	500[a]	0.65	1.65
Steam turbine	10.3 MW_e	0.7	3.1
Grinding	33.5[b]	0.6	0.41

a= 500 dry tonnes of biomass input per day, c=kmol of CO_2 removed, b=33.5 wet t h^{-1} of biomass input,

Table 5. Direct, indirect and operating costs associated with process design

Direct and Indirect costs [27]	
Installation	0.39×EC
Instrumentation and controls	0.13×EC
Piping	0.31×EC
Electrical	0.1×EC
Buildings	0.29×EC
Yard improvements	0.1×EC
Land	0.06×EC
Engineering	0.32×EC
Construction Expenses	0.34×EC
Contingency	0.36×EC
Contractor's Fee	0.18×EC
Start up	0.1×EC
Fixed capital Investment (FCI)	**EC+DC+ID**
Working Capital	0.15×EC
Total Capital Investment (TCI)	**FCI + Working capital**
Operating costs [25, 28]	
Utility and Chemicals	**Cost ($)**
Feedstock price	10 t^{-1}
Labour	30,000 per labour
Ash Transport	62 t^{-1}
Ash Disposal	24 t^{-1}
Feed Boiler Water	0.15 m^{-3}
Electricity	0.07 kWh^{-1}
Process steam	0.018 kWh^{-1}
Cooling Water	0.07 kWh^{-1}

when comparing the financial feasibility between different conversion pathways. Furthermore, it is extremely useful when the value of a product cannot be determined clearly, for instance when a known product is produced from a nonconventional feedstock (as in this case) **[29]**.

$$Cost\ of\ electricity\ (COE) = \frac{Total\ Annual\ Cost\ (TAC)}{Annual\ electricity\ output} \quad (8)$$

Where the *TAC* derives from the sum of the annualised capital cost (*ACC*) and the operating costs. **Eq. (9)** is utilised for the calculation of the *ACC* where i is the interest rate (equal to 7%) and n the lifetime of the project (equal to 25 years) **[30]**.

$$ACC = TCI \times \frac{i\times(1+i)^n}{-1+(1+i)^n} \quad (9)$$

Based on the calculations, electricity is produced from the examined IGCC system at a rate of 0.071 $ kWh^{-1}. This value is rather higher than the 0.054 $ kWh^{-1} **[31]** achieved through combustion mainly due the higher investment costs (both capital and operating expenditures).

Table 6. Economic results

	IGCC	**Combustion [28]**
TCI ($ kWh^{-1})	0.41	0.23
ACC ($ kWh^{-1})	0.029	0.02
OC ($ kWh^{-1})	0.042	0.034
COE ($ kWh^{-1})	0.071	0.054

3.5. *Effect of the plant size*

In addition, the effect of the plant size on electricity production cost was investigated. This was done by varying the input mass flow rate of bagasse. The results of this analysis are presented in **Figure 6**. A second order decay trend can be observed for the production cost as the plant size increases. Beyond the baseline, the production cost slope levels out at a value of approximately 0.06 $ kWh^{-1}. The economies of scale favour the profitability of the process, but one obstacle to this transition is the feedstock availability, since bagasse production is, of course, limited by the capacity of the plant from which it is a by-product. The equation utilised is the following **[32]**:

$$\text{production cost} = \text{base production cost} \times \left(\frac{\text{feedstock rate}}{\text{base feedstock rate}}\right)^{(1-\frac{1}{f})} \quad (10)$$

Where f is the scale economic parameter and its suggested value for power generation technologies is 0.85 **[33]**.

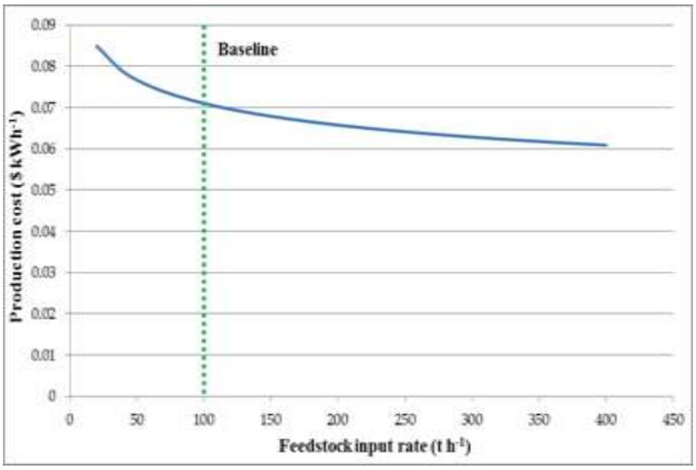

Fig. 6. Effect of plant size on the electricity production cost

4. Concluding Remarks

The aim of the present study was to develop a techno-economic model regarding the exploitation of bagasse via the IGCC technology. Aspen plus simulator was employed to simulate the process and based on the simulations technical and economic evaluations were conducted. The proposed system generates electricity at a rate of 112 MW and the resultant cost of electricity is 0.071 \$ kWh^{-1}. This value is higher than the one obtained from direct combustion. In general, gasification is a more efficient, cleaner electricity process that is a preferred option from an efficiency and emissions point of view. However, it is a more complicated technology associated with increased initial costs and operating costs. Gasification requires very accurate monitoring of system inputs for the appropriate chemical reactions to take place and supplementary equipment or design alterations to accomplish emission controls **[34]**. It takes highly skilled personnel to manage the process. These elements escalate the operation expenditure of a gasification plant. These higher expenditures presently counterbalance the greater efficiency of the process and thereby electricity is produced more economically via combustion. However, gasification process will become much better understood and much more accepted in the foreseeable future. Recent advances, including short residence time and air blown gasifiers, combinations of membrane types and new classes of gas turbines, focus on the cost reduction of the IGCC process and it is predicted that, in the next ten years, the cost benefit analysis will favour the gasification instead of the direct combustion **[35]**.

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