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Research Article

Energy Analysis of Utilizing Biomass Gasification to Partially Substitution Fossil Fuels in an IBG-GT-ST-Kalina Cycle

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ABSTRACT

In this study, the partial alteration of fuel consumption of combined cycle power plants was investigated and analyzed using an innovative model. This system is applicable using the fuel derived from the biomass gasification process. For this purpose, energy modeling of an advanced gasification system to supply a share of the gas fuel was fulfilled. The results demonstrated that by considering the reasonable capacities for the design, up to 10 % of natural gas fuel could be replaced with syngas. In addition, heat recovery of the plant stack in the Kalina low-temperature cycle enhanced the total efficiency by up to 1.7 %. Therefore, the competitive advantage of the proposed cycle was enhanced compared to conventional power generation systems. A parametric study of the components affecting the integrated cycle performance including alternative biomass fuels, moisture content of biomass fuel, steam-to-biomass ratio, and equivalence ratio of the gasifier was performed, and the permissible values of each factor were obtained. Thus, by utilizing the proposed approach, it is possible to gradually substitute the consumed fossil fuels of power plants with renewable resources to achieve the objectives of sustainable energy development.

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1. INTRODUCTION

Gasification, considered a significantly high-efficiency technology for thermo-chemical conversion of biomass, has been converted into a promising approach to generating energy from solid waste [1-3]. Gasification is implemented using a gasifying agent (oxygen, air, or steam) to convert biomass into combustible synthesis gas through the reduction process at high temperatures (around 800-1000 °C) [1, 4]. Syngas includes methane, hydrogen, carbon monoxide, carbon dioxide, water steam, and unfortunate by-products. Each component concentration pertains to oxidant (i.e., gasifying agent), conditions of the process such as temperature and pressure, use or non-use of catalysts or sorbents like CO_2 capturing process, design of the gasifier, residence time of components, and feedstock composition [1, 5-9]. Furthermore, several types of gasifiers are used depending on the operating conditions and the type of biomass fuel. For instance, Rahman et al. [10] designed and implemented a low-tar downdraft biomass gasifier connected to a power generation system. The optimum equivalence ratio lies between 0.29 and 0.41 for the best performance of the mentioned gasifier. Using mass and energy balances, the average gasifier capacity and cold gas efficiency are about 23.1 kW and 82.7 % for wood chips, whereas they are 33.1 kW and 60.5 % for wood pellets. Sorbents in the shape of CaO might cause a shift to the thermodynamic equilibrium and increase the H_2 content up to 90 %. Therefore, different efforts have been made through simulation models such as mathematical programming to achieve a significant progress in performance prediction. An accurate presentation of the chemical and physical attributes of various gasifier types facilitates an evaluation of syngas composition or formation of an optimized biomass gasifier plant for green power supply prospects [11-13].

Figure 1 shows how to technically design and implement the concept of Fast Internal Circulated Fluidized Bed (FICFB) gasifier. Biomass is first gasified in the gasification reactor and the ungasified char is combusted in the FB combustion reactor. Therefore, biomass is burned to heat the substrate material. Particles of hotbed material are separated from the flue gas in the cyclone separator. Hot particles are transported to the gasifier through a sealed tube. The sealing of this area is to prevent gas leakage between the gasification and the combustion zone and to provide a desirable solid exit of the system.

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The input biomass is transferred directly to a bubble fluidized bed gasification reactor by screw conveyors. In this chamber, several processes are performed in parallel. These processes include drying, volatilization, heat decomposition, and somewhat heterogeneous gasification. The bed temperature is set at 850 to 900 °C. The remaining char from the gasifier and the bed material is removed from the combustion zone in this system through a sloping channel [14-16].

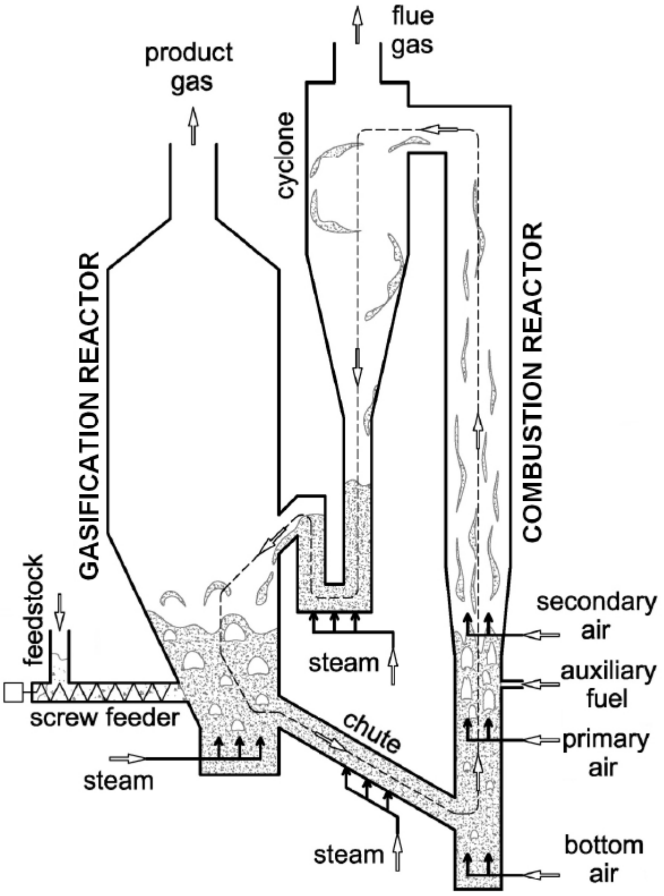

Figure 1. Fast Internal Circulating Fluidized Bed (FICFB) steam gasifier [14]

According to the study results (as shown in Table 1), the electricity generation potential of municipal waste, solid biomass (wood), and agricultural residues were calculated for Iran until 2050. Its results indicate that the full potential will be around 23.7 TWh y^{-1}, equivalent to 3390 MW of power plants [17]. Moreover, Azizaddini et al. [18] demonstrated that the potential of available biomass resources in Iran was about 51 TWh, which is applicable to about 1400 MW of rural gasification power plants to 2300 MW of advanced gasification power plants.

In addition, low-temperature cycles that operate with different working fluids are conveniently suitable for recovering heat from steam turbines at small and medium power plants in the capacity range of hundreds of kilowatts. In fact, instead of water, organic chemicals with desirable thermodynamic properties are used in these cycles so that the enthalpy drop is much lower. Therefore, the flow can be expanded in several stages in the turbine [19, 20].

Rentizelas et al. [21] compared two types of power generation systems including biomass-fueled boiler-ORC and biomass gasifier-stirling engine. Their results indicate that the generated electricity in the gasification cycle is more than three times that of the boiler cycle. Moreover, they indicate that the application of gasification instead of a biomass combustion system woud lead to many economic advantages.

In another study, Kalina [22] examined three arrangements for a small-scale power generation cycle including the downdraft biomass gasifier, gas engine, and organic Rankine cycle. The results indicated that the lowest energy efficiency of 23.6 % was obtained for the simple cycle, while the highest efficiency of 28.3 % was calculated for the dual ORC configuration.

Puig-Arnavat et al. [23] presented and compared five different arrangements for trigeneration cycles including electricity generation, heating, and cooling applying biomass gasification. The capacity of the studied cycles in the range of 250 kW to 2 MW was considered. The highest equivalent energy efficiency of 42.7 % was obtained for an arrangement that used the generated steam by the heat recovery system in a double-effect absorption chiller.

Table 1. The biomass electricity potential from agricultural waste (mainly bagasse), wood, and municipal waste in Iran until 2050

	Municipal wastes						**Wood wastes**	**Agricultural wastes**	**Total**
Year	2000	2010	2020	2030	2040	2050	2050	2050	2050
Biomass electricity potential (TWh y^{-1})	7.44	9.33	11.46	13.03	14.69	15.94	7.3	0.46	23.7

Fortunato et al. [24] proposed some schemes of the integrated power plant using biomass gasification as an alternative fuel. The presented solutions were based on two different regeneration scenarios and their results were compared. The results demonstrated the ineffectivenss of the extra combustor for regeneration. This study suffers from the simplicity of the mathematical model to solve complex thermodynamic cycles and the failure to consider essential components in the parametric analysis of gasifier, providing the entire system capacity with biomass fuel (in some months of the year), the feasibility of more efficient heat recovery, and use of low-temperature cycles for the cogeneration system.

As can be deduced from the findings mentioned above, it is not possible to replace biomass fuels with fossil fuels at conventional power plants at once. Therefore, the present study investigates the use of biomass fuels (with a reasonable and practical share) in the case of conventional power generation systems, especially for regions like Iran that benefit from natural gas. Previous studies have failed to comprehensively address this issue in countries with enormous oil and natural gas resources. Thus, gradual elimination of fossil fuels and development of renewable resources, as the objectives of sustainable energy development, can be considered two of the innovative research achievements.

In addition, this study investigated the increase in the power of the proposed power plant using a low-temperature Kalina cycle. This point is essential because upon increasing the power and output efficiency of power generation systems using renewable energies, their competitiveness and acceptance will grow. Hence, another innovation of the present study is the proposition of an integrated cycle alongside the attempt at analyzing its capacity, constraints, and technical aspects.

2. SYSTEM DESCRIPTION

2.1. Base cycle

Figure 2 shows the base combined cycle consisting of a fluidized bed biomass gasifier, a gas turbine, and a steam turbine. The produced syngas from the biomass gasification process is consumed as fuel in the combustion chamber of the gas turbine. An auxiliary fuel source is also considered in this study to be used in insufficient syngas to produce power with the capacity intended for the combined cycle. Flue gases from gasifier and gas turbine generate the required steam of the steam turbine in the Heat Recovery Steam Generator (HRSG).

2.2. Biomass choice and characteristics

The chosen biomass is wood chips due to waste biomass. It is of low price (20-60 € t^{-1}) and shows a favorable agricultural and industrial by-product in diverse climate conditions [25]. The chemical characteristics of wood chips point to the sizeable lignocellulosic sector of the biomass. Generally, a dry and ash-free basis composition consists of 40-55 % of C, 35-45 % of O_2, 5-7 % of H_2, less than 1 % of N_2, Cl, and S, and less than 10 % ashes [26]. The composition values of the selected wood chips are shown in Table 2.

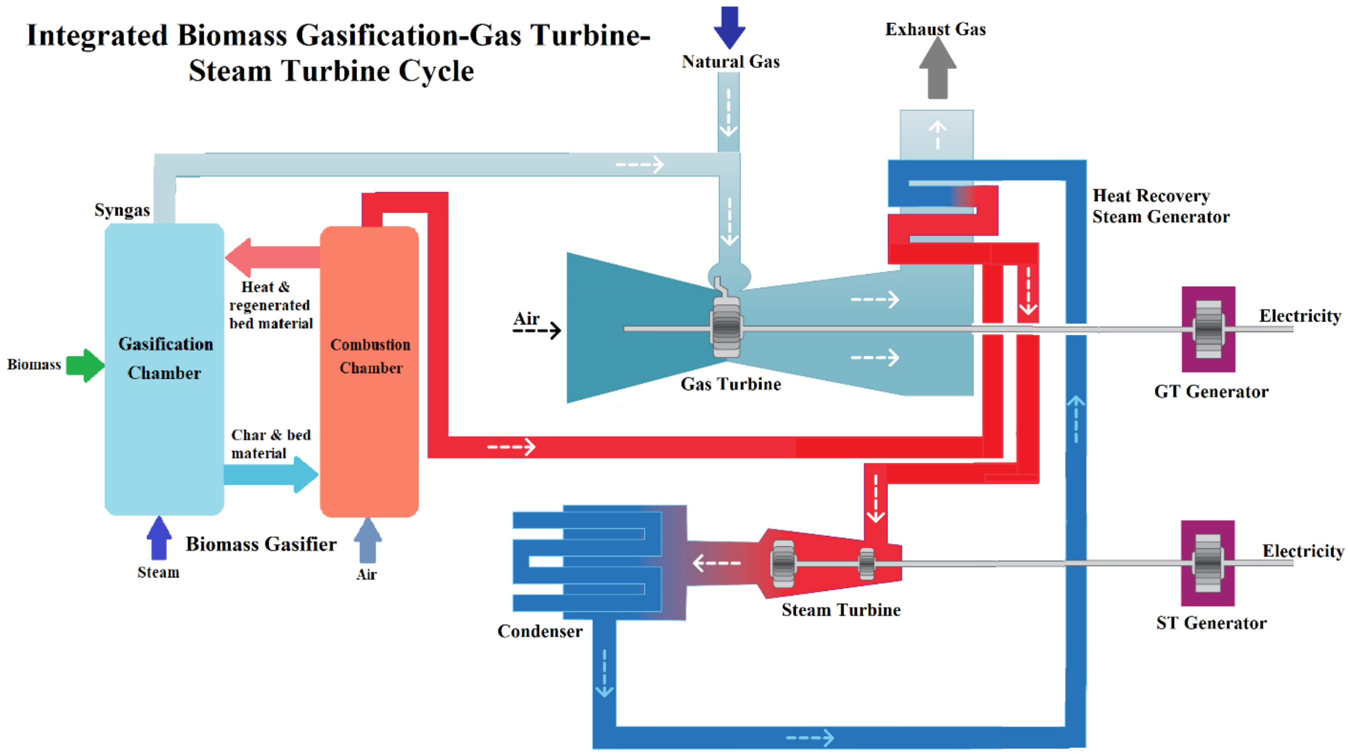

Figure 2. Schematic of the main proposed IBG-GT-ST cycle

Table 2. Dry composition of the selected wood chip biomass used in this study [27]

Component	Mole Fraction
C	50.6 %
H	6.5 %
O	42.0 %
N	0.2 %
S	0.0 %
Ash	0.7 %
HHV	19.6 MJ kg^{-1}

2.3. IBG-GT-ST-Kalina cycle

In this cogeneration scenario, the heat recovered from the exhaust of the topping combined cycle is consumed to generate electricity in the Kalina cycle as a low-temperature power system. According to Figure 3, the working fluid, a binary ammonia-water mixture, absorbs the flue gas heat in the evaporator. The working fluid at the evaporator outlet (State 5) is biphasic and therefore, separates into liquid (state 7) and vapor (state 6) at the separator. The vapor leaving the separator expands to generate electricity in the turbine. The liquid leaving the separator transfers its heat in the regenerator to the working fluid before entering the evaporator (State 4). Then, the pressure of the regenerator outlet fluid in the throttle valve is reduced (State 9) and mixed with the turbine outlet fluid in the absorber (State 1). The temperature of the mixture is reduced in the condenser and it returns to the required operating pressure by the pump.

3. MODELING APPROACH AND ASSUMPTIONS

Mathematical modeling of the proposed cycles was performed using thermodynamic relations to calculate mass and energy balance, output power and efficiencies, and other principal parameters in EES software.

Equilibrium modeling of the gasification process is divided into two methods: stoichiometric and non-stoichiometric forms. The stoichiometric approach requires a reference reaction that covers all available reactions and gases and is modeled based on this reaction. In the non-stoichiometric method, there is no reference reaction. The only input required by the model is the final biomass analysis to find the composition and calorific value of the produced synthesis gas. Many researchers believe that stoichiometric and non-stoichiometric methods are equivalent in modeling value.

In this research, the non-stoichiometric method is used and in a thermodynamic model, the following are assumed:

1. The circulating fluidized bed reactor is assumed to be dimensionless and it does not need to be designed.

2. Heat loss in the reactor is negligible.

3. Temperature distribution is uniform and complete mixing of materials occurs.

4. Sufficient residence time is considered to reach equilibrium.

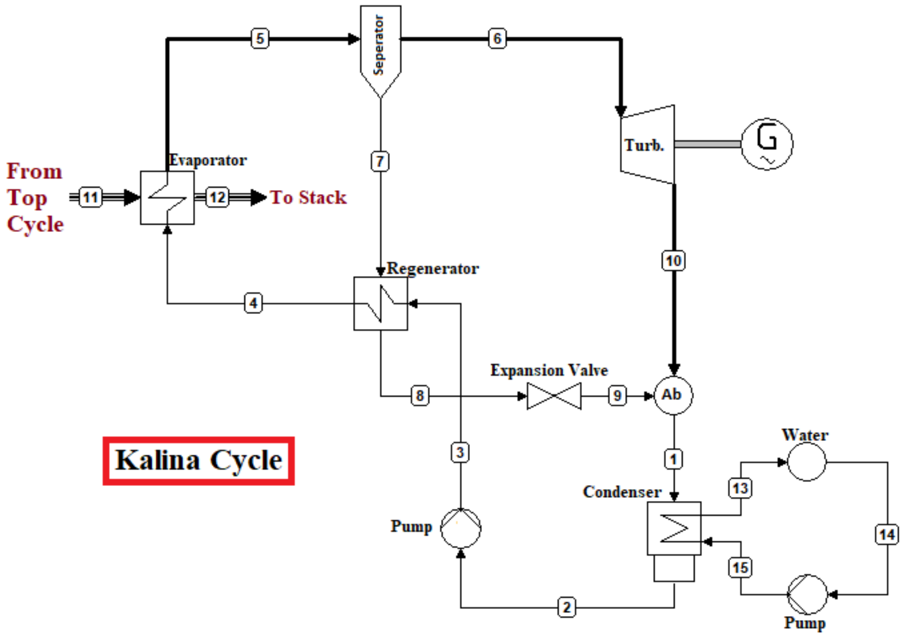

Figure 3. Schematic of the modeled Kalina cycle

A Siemens twin-shaft industrial gas turbine SGT-400 and a Siemens steam turbine SST-110 have been considered in this study with the nominal power generation capacities of 12.9 MWe and 7 MWe, respectively [28, 29].

The following assumptions are defined to implement the energy model:

1. All the proposed cycles operate in a steady-state condition;

2. Pressure drops in all heat exchangers and pipes are ignored.

3. The isentropic efficiencies of pumps and turbines are constant.

4. Changes in potential and kinetic energies are ignored.

The produced gas's Lower Heating Value (LHV) is estimated from the standard low calorific values (MJ kg^{-1}) of the syngas characteristics. For instance, 120 MJ kg^{-1}, 10 MJ kg^{-1}, and 50 MJ kg^{-1} for H_2, CO, and CH_4 are mainly considered based on their mass concentrations in the whole produced gas.

The gasifier model operation conditions are presented in Table 3.

Table 3. Input parameters of the proposed biomass gasifier

Parameter	Value	Unit
Biomass moisture content	14	[wt %]
Steam-to-biomass ratio	0.5	-
The temperature of biomass fuel at feedstock	298	[K]
Biomass inlet flowrate	0.1	[kg s^{-1}]

The considered reactions in the proposed simulation are shown in Table 4. The gasifying agent is steam in this study. Steam gasification is usually implemented via a fluidized bed gasifier that can provide material recirculation to prepare the required heat of gasification reactions. Afterward, the design of the gasifier reactor might be a regular cylinder. Other descriptions could be found in the research executed by Di Carlo et al. [30].

The governing equations of a gasifier with air or steam agent are presented. The ratios of biomass chemical components can be expressed as $C_xH_yO_zN_wS_v$, where v, w, z, y are the molar ratios of hydrogen to carbon, oxygen to carbon, and nitrogen to carbon, and sulfur to carbon in the biomass, respectively [32].

$$C_xH_yO_zN_wS_v + \alpha H_2O + \beta(O_2 + 3.75N_2) \rightarrow a_1CO_2 + a_2CO + a_3H_2 + a_4H_2O + a_5CH_4 + a_6N_2 + a_7SO_2 + \text{tar} \quad (1)$$

a_i represents the number of moles of gaseous components leaving the gas generator, β is the amount of air per kilomole of biomass feed, and α the kilogram of moisture per kilomole of biomass feed. Tar production calculations are neglected in the present study.

The coefficients of the products of production a $(a_1.a_2.a_3.\dots.a_7)$ are unknown, and to obtain them, the Gibbs function of the products must reach the minimum possible value. On the other hand, the following equations are accepted according to the mass balance.

$$x = a_1 + a_2 + a_5 \quad \text{Carbon balance} \quad (2)$$

$$y + 2\alpha = 2a_3 + 2a_4 + 4a_5 \quad \text{Hydrogen balance} \quad (3)$$

$z + \alpha + 2\beta = 2a_1 + a_2 + a_4 + 2a_7$ Oxygen balance (4)

$w + 7.5\beta = 2a_6$ Nitrogen balance (5)

$v = a_7$ Sulfur balance (6)

$$x = 1 \quad (7)$$

$$a_8 = a_1 + a_2 + a_3 + a_4 + a_5 + a_6 \quad (8)$$

There are a total of 7 equations and ten unknowns. Therefore, the function must be minimized for several dependent variables, which can be three of $(a_1.a_2.a_3.\ldots.a_7)$.

The Gibbs function for SO_2, H_2O, H_2, CO_2, CO is obtained and finally, the relation is calculated through the following equation.

$$Gibbs_{fun} = a_1 g_{CO2} + a_2 g_{CO} + a_3 g_{H2} + a_4 g_{H2O} + a_5 g_{CH4} + a_6 g_{N2} + a_7 g_{SO2} \quad (9)$$

This general function must be minimized for the three independent variables a_1, a_2, a_3.

It should be noted that minimizing the Gibbs function can be used only when the temperature of the products is known.

$$\frac{\Delta G}{RT} = -\ln(K) \quad (10)$$

Table 4. Gasification reactions [31]

Reaction	Reaction name	Heat of reaction	Reaction number
Combustion reactions			
$C + 0.5\,O_2 \rightarrow CO$	Char partial combustion	-111 MJ kmol^{-1}	R1
$CO + 0.5\,O_2 \rightarrow CO_2$	CO partial combustion	-283 MJ kmol^{-1}	R2
$H_2 + 0.5\,O_2 \rightarrow H_2O$	H_2 partial combustion	-283 MJ kmol^{-1}	R3
Heterogeneous reactions			
$C + H_2O \leftrightarrow CO + H_2$	Water-gas	+131 MJ kmol^{-1}	R4
$C + CO_2 \leftrightarrow 2CO$	Boudouard	+172 MJ kmol^{-1}	R5
$C + 2H_2 \leftrightarrow CH_4$	Methanation	-75 MJ kmol^{-1}	R6
Homogeneous reactions			
$CO + H_2O \leftrightarrow CO_2 + H_2$	Water gas-shift	-41 MJ kmol^{-1}	R7
$CH_4 + H_2O \rightarrow CO + 3H_2$	Steam-methane reforming	+206 MJ kmol^{-1}	R8

In this case, another indeterminate variable, temperature, is added to the equations and the dimension ΔG is written for the significant gas equations including the Baudouard reaction equation, the water-gas reaction, and the methane reactions. This method assigns a value to the Gibbs function in standard conditions (pressure and temperature). The enthalpy value is also obtained using this method. Finally, the energy balance is obtained by solving the following equation.

$$h_r = h_{f_{Biomass}} + \alpha h_{H_2O} + \beta h_{O2} + \beta(3.76 h_{N2}) \quad (11)$$

$$h_p = a_1 h_{CO2} + a_2 h_{CO} + a_3 h_{H2} + a_4 h_{H2O} + a_5 h_{CH4} + a_6 h_{N2} + a_7 h_{SO2} \quad (12)$$

$$h_r = h_p \quad (13)$$

h_r is the enthalpy of the reactants and h_p is the enthalpy of the products.

The two thermodynamic parameters commonly used to investigate gasification operations are the calorific value of the synthesis gas and the cold gas efficiency, obtained from the following equations.

$$h_{f_{Biomass}} = LHV_{dry} + \left(\frac{1}{M_{bio}}\right)\left(a_1 h_{CO} + a_2 h_{CO_2} + a_3 h_{H_2} + a_4 h_{H_2O} + a_5 h_{CH_4} + a_6 h_{N_2} + a_7 h_{SO_2}\right) \quad (14)$$

$$LHV_{gas} = \left(\left(\frac{a_1}{M_{bio}}\right) LHV_{CO} + \left(\frac{a_3}{M_{bio}}\right) LHV_{H_2} + \left(\frac{a_5}{M_{bio}}\right) LHV_{CH_4}\right) \quad (15)$$

$$CGE = \frac{\frac{a_8\,RT_0}{p_0} LHV_{gas}}{M_{bio} LHV_{bio}}\ (\%) \quad (16)$$

Hydrogen is the desired product in this process and the efficiency of hydrogen production can be described as system efficiency in general or Equation 17:

$$\eta_{H_2} = \frac{\dot{m}_{H_2} LHV_{H_2}}{M_{bio} LHV_{bio}}\ (\%) \quad (17)$$

Equivalence Ratio (ER) indicates air-to-biomass ratio and plays an essential role in biomass gasification. When the ER value is reduced, the share of H_2 and CO in the synthesized gas increases [33].

Higher ER leads to less H_2 and CO and more CO_2, which increases the amount of heat in the synthesized gas due to increased oxygen reactions. ER is also affected by moisture and raw biomass volatiles. If biomass water is higher than 15 %, it increases the ER and the amount of gas. More volatiles in biomass increase tar production.

Steam to biomass ratio (S/B) is an essential parameter in gasification because it affects the volume of synthesized gas and its calorific value. Increasing the vapor ratio increases H_2 and increases the calorific value of the synthesized gas. It also reduces bitumen production due to water-gas change reactions, but the value of S/B can be increased to some extent because this increase causes excess steam vapor in the synthesized gas. Reducing the enthalpy in the production of this excess steam reduces the efficiency of this process; ths, this ratio should be optimal.

The modeling process for solving the gasification equations is presented in Figure 4.

The electrical efficiency of the integrated cycle is obtained by Equation 18:

$$\eta_{Electrical,IC} = \frac{\dot{W}_{GC} + \dot{W}_{SC} + \dot{W}_{BC}}{\dot{Q}_{in}} \quad (18)$$

where $\eta_{Electrical,IC}$ presents the electrical efficiency of the integrated cycle, $\dot{W}_{GC}$, $\dot{W}_{SC}$, and $\dot{W}_{BC}$ are the gas cycle, steam cycle, and bottoming cycle delivered power, and $\dot{Q}_{in}$ is the supplied heat by fuels (biomass and natural gas).

Some of the critical equations of gas cycle calculations are presented in Table 5 [34].

The main equations of steam cycle calculations are given in Table 6 [35]. Table 7 shows the initial values for base combined cycle modeling.

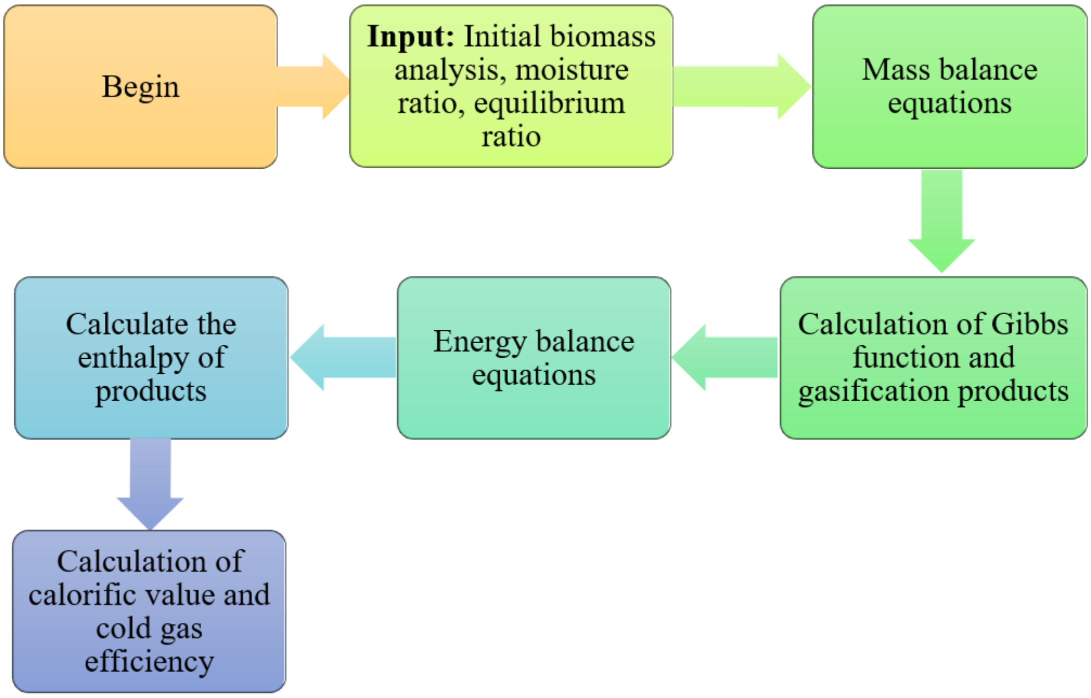

Figure 4. The modeling process of the gasification equations in the present study

Table 5. The main equations of the gas cycle

Parameter	Equation	Description	No.
Heat rate	$\text{Heat rate} = \frac{3412(\text{Btu/kWh})}{\eta_{Prime}}$	η_{Prime} is the GC thermal efficiency defined by manufacture	(19)
Actual air flow rate	$\dot{m}_{actual} = \dot{m}_{theoritical} \times \text{Excess Air}$	Excess air is defined as input data	(20)
GC net delivered power	$\dot{W}_{GC,net} = \dot{W}_{turbine} - \dot{W}_{compressor}$	-	(21)
GC net efficiency	$\eta_{GC,net} = \frac{\dot{W}_{GC,net}}{\dot{Q}_{in}}$	$\dot{Q}_{in}$ is the supplied heat by fuel	(22)

Table 6. The main equations of the steam cycle

Parameter	Equation	Description	No.
Flue gas enthalpy	$\dot{m}_{Flue\,gas} . h_{Flue\,gas} = (\dot{m}_{GT,out} . h_{GT,out}) + (\dot{m}_{gasifier\,combustor,out} . h_{gasifier\,combustor,out})$	Gasifier combustor components are H_2O, CO_2, N_2, SO_2	(23)
Duct burner outlet flow rate	$\dot{m}_{Duct\,burner,out} = (\dot{m}_{Flue\,gas} + \dot{m}_{Fresh\,air} + \dot{m}_{Auxiliary\,fuel})$	The duct burner is activated if the flue gas enthalpy is not enough.	(24)
SC net delivered power	$\dot{W}_{SC,net} = \dot{W}_{turbine} - \dot{W}_{pump}$	-	(25)
SC net efficiency	$\eta_{SC,net} = \frac{\dot{W}_{SC,net}}{\dot{Q}_{in}}$	$\dot{Q}_{in}$ is the supplied heat by flue gas	(26)

Table 7. Initial values of the base combined cycle

Parameter	Value	Unit
Specific heat capacity of flue gas in GC [36]	1.185	[kJ (kg K)$^{-1}$]
Reference temperature when the enthalpy and entropy are assumed zero	273	[K]
Reference pressure when the enthalpy and entropy are assumed zero	1.013	[bar]
Specific heat capacity of air	1.005	[kJ (kg K)$^{-1}$]
Specific heat capacity of fuel	1.148	[kJ (kg K)$^{-1}$]
Air heat capacity ratio	1.4	-
Natural gas heat capacity ratio	1.333	-
Universal gas constant	8314	[J (kmol K)$^{-1}$]
The pressure of inlet water into the cycle	101.3	[kPa]
The temperature of inlet water into the cycle	20	[°C]
The outlet temperature of the steam turbine	54	[°C]

To calculate natural gas fuel conservation by biomass consumption in the combined cycle, the equivalence biomass flow rate has been considered in Equation 27. Therefore, fossil fuel conservation could be obtained.

$$\dot{m}_{eq,biomass} = \frac{(\dot{m}_{syngas} \times LHV_{syngas})}{LHV_{fuel,GC}} \quad (27)$$

$$\dot{m}_{fuel\,conservation} = \frac{(\dot{m}_{eq,biomass})}{LHV_{fuel,GC}} \quad (28)$$

Then, by placing the integrated cycle flow rate in Equation 30, the combined cycle efficiency is calculated.

$$\dot{m}_{IC} = (\dot{m}_{fuel,GC} - \dot{m}_{eq,biomass}) \quad (29)$$

$$\eta_{IC} = \frac{(\dot{W}_{net,CC})}{(LHV_{biomass} \times \dot{m}_{biomass} \times 1000) + (\dot{m}_{IC} \times LHV_{fuel,GC})} \quad (30)$$

The mass balance of the Kalina cycle working fluid is represented by Equation 31:

$$\sum(\dot{m}_{in}.x) = \sum(\dot{m}_{out}.x) \quad (31)$$

In this equation, x represents the amount of ammonia concentration in the ammonia-water mixture.

The absorbed heat in the evaporator is obtained by Equation 32:

$$q_{Evaporator} = h_{Evaporator,out} - h_{Evaporator,in} \quad (32)$$

Also, dissipated heat in the condenser is presented by the following equation:

$$q_{Condenser} = h_{Condenser,out} - h_{Condenser,in} \quad (33)$$

The net Kalina delivered power can be evaluated by Equation 34:

$$\dot{W}_{Kalina,net} = \dot{W}_{Turbine} - \dot{W}_{Pumps} \quad (34)$$

Furthermore, the energy efficiency of the Kalina cycle is shown in Equation 35 [22]:

$$\eta_{Kalina} = \frac{\dot{W}_{net,Kalina}}{\dot{Q}_{Evaporator}} \quad (35)$$

4. RESULTS AND DISCUSSION

4.1. Biomass gasifier

Syngas composition is compared in Table 8 with the generated results of the previous studies according to the literature data including findings of Fercher et al. and Hofbauer et al. [37-39] at an S/B of 0.5. It should be noted that all components of the produced gas have been considered in modeling pertainig to the written values in this Table.

Table 8. Comparison of syngas characteristics with experimental and mathematical studies

S/B = 0.5 ($kg_{steam}/kg_{biomass}$)	Literature Data [37, 38]	Literature Data [40]	Current Study
H_2 (% dry mole fraction)	30-40	42.2	41.9
CO (% dry mole fraction)	20-30	22.9	23.3
CO_2 (% dry mole fraction)	15-25	21.8	21.7
CH_4 (% dry mole fraction)	8-12	13.1	7.3
LHV (MJ kg^{-1})	14.1-15.2	14.2	15.8

According to the comparison made in Table 8, it is discussed that due to the use of catalysts in the experimental study of References 37 and 38, the water-gas shift reactions and steam methane reforming are presented in relations, R7 and R8, producing less carbon monoxide and carbon dioxide. However, the results obtained from this study and Reference 40 have been adjusted based on the equilibrium conditions of gasification and the correction coefficients of the FICFB biomass gasifier system, causing a slight difference between the results. Thus, it is clear that the model proposed in the present study has acceptable validity.

Of note, fluidized bed gasifiers operate in unstable temperature conditions due to their turbulent conditions, and simple models cannot achieve high-precision responses. Therefore, the reasonable accuracy of the model presented in this study is confirmed.

4.2. Combined cycle

The results of the main parameters of the base cycle are presented in Table 9. The total delivered power of the cycle is 17.94 kW. The results indicate acceptable conformity to the details published by the manufacturer of gas and steam turbines [28, 29].

Table 9. Results of the base proposed combined cycle

Parameter [Unit]	Value
Gas cycle	
Heat rate [Btu kWh^{-1}]	9805
Inlet GC fuel flowrate [kg s^{-1}]	0.8147
Inlet GC air flowrate [kg s^{-1}]	37.14
Compressor outlet temperature [K]	661.3
Flue gas mass flow rate [kg s^{-1}]	38.08
Steam cycle	
Inlet feed water pump flowrate [kg s^{-1}]	5.1
HP steam demand [kg s^{-1}]	5
HP steam produced [kg s^{-1}]	6.122
Temperature in A [K]	837
Temperature in C [K]	538.5
Power and Efficiencies	
Gas cycle net delivered power [kW]	12,850
Steam cycle net delivered power [kW]	5090
Gas cycle efficiency [%]	34.67
Steam cycle efficiency [%]	13.74

4.3. Kalina cycle

The proposed integrated power system results based on the Kalina cycle are presented in Table 10. Also, the thermodynamic values for all nodes of the Kalina cycle are shown in Table 11.

According to the modeling results given in Table 10, the utilization of the Kalina cycle leads to the improvement of the total cycle power by approximately 1.7 %.

Table 10. The results of the IBG-CC-Kalina modeling

Parameter	Value	Unit
Integrated cycle efficiency	52.58	[%]
Kalina cycle efficiency	19.82	[%]
Integrated cycle net delivered power	18,535	[kW]
Kalina expander delivered power	620	[kW]
Kalina cycle net delivered power	592	[kW]

Table 11. The thermodynamic values of each node of the Kalina cycle in the proposed integrated cycle

State	T (K)	P (bar)	x (%)	m (kg s^{-1})
1	315.3	10.74	95	2.5
2	302	10.74	95	2.5
3	303.8	80	95	2.5
4	309.8	80	95	2.5
5	426.2	80	95	2.5
6	426.2	80	96.54	2.38
7	426.2	80	64.31	0.1195
8	307.8	80	64.31	0.1195
9	308.9	10.74	64.31	0.1195
10	314.2	10.74	96.54	2.38
11	433.5	1	-	38.08
12	423.5	1	-	38.08

4.4. Parametric study

4.4.1. Steam to biomass ratio

Figure 5 shows the outcome of parametric analysis for the proposed model by changing the S/B ratio from 0.1 to 0.9 and the gasifier temperature is 820 °C.

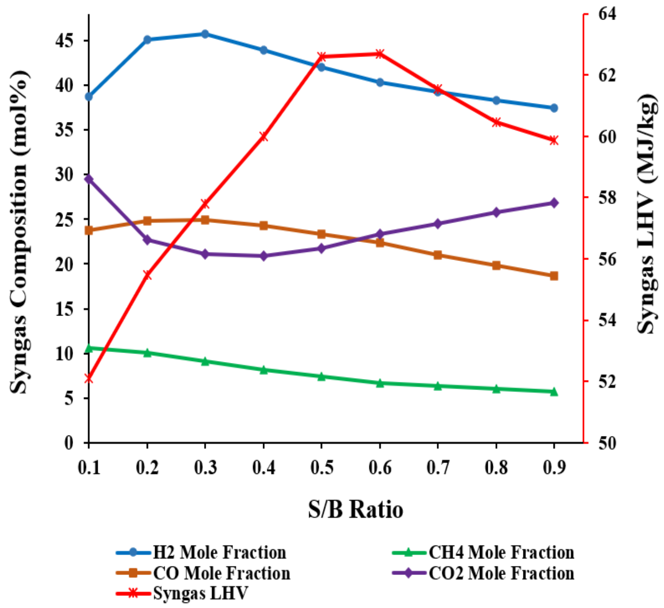

Figure 5. Syngas composition and LHV changes relative to steam-to-biomass ratio variation in the proposed combined cycle

Given the formula observed for calculating LHV (Equation (15)) [41], the coefficient corresponding to the molar fraction of CO is higher than that of H_2. Therefore, the LHV decreases as SB increases, as shown in Figure 5, in a wide range of SB ratios. It can be seen that increase in H_2 is always followed by a decrease in CO and an increase in CO_2. Hence, the value of the SB ratio should not be too large, especially at high gasification temperatures.

4.4.2. Alternative fuels

To conduct a technical feasibility study and compare the effectiveness of alternative biomass fuels, three agricultural and horticultural biomass fuels were considered as the input of the proposed gasifier system in this study. These fuels include two types of gardens pruning wastes and sugarcane bagasse. The specifications of alternative fuels and the results obtained for the base cycle are given in Table 12 [42].

Table 12. Mole fraction of the selected alternative biomass fuels

Component	Garden Prunings #1	Garden Prunings #2	Bagasse
C (% dry mole fraction)	51.02	50.38	46.96
H (% dry mole fraction)	6.41	6.2	5.72
O (% dry mole fraction)	35.63	35.38	44.05
N (% dry mole fraction)	0.64	0.86	0.27
S (% dry mole fraction)	0.0	0.0	0.02
Cl (% dry mole fraction)	0.0	0.0	0.04
Ash (% dry mole fraction)	6.3	7.18	2.94
Moisture Content (%)	10	10	10
HHV (MJ kg^{-1})	19.48	19.26	18.5

The results obtained from modeling the base cycle for the primary and alternative fuels are shown in Table 13. The use of wood chip fuel in the gasifier exhibits better results than other alternative fuels due to its higher calorific value. However, the results of this study prove that the application of biomass fuels will save more than 8 % in natural gas consumption at the proposed power plant.

Table 13. Results of the base proposed combined cycle for the selected biomass fuels

Parameter [Unit]	Wood Chips	Garden Prunings #1	Garden Prunings #2	Bagasse
Natural Gas fuel conservation by using biomass [kg s^{-1}]	0.08288	0.07754	0.07447	0.07011
Natural Gas fuel conservation rate [%]	10.17	8.51	8.14	8.60
Duct burner fuel flowrate [kg s^{-1}]	-0.0428	-0.0424	-0.0429	-0.0428
Duct burner input air flowrate [kg s^{-1}]	-0.5397	-0.5416	-0.5418	-0.5401
High heating value of biomass [MJ kg^{-1}]	20.96	20.14	19.72	17.27
Low heating value of cold gas [kJ kg^{-1}]	15,867	13,117	15,733	16,203
Low heating value of syngas ($CO+CH_4+H_2$) [kJ kg^{-1}]	52,352	49,524	49,522	48,434
Biomass molar weight [kg $kmol^{-1}$]	23.57	22.06	22.13	24.81
Produced gas molar weight [kg $kmol^{-1}$]	8.873	8.409	8.282	8.12
Syngas mass flowrate ($CO+CH_4+H_2$) [kg s^{-1}]	0.07908	0.07124	0.06842	0.06587
Gasification temperature [°C]	821	714	696	797
Gasifier cold-gas efficiency [%]	79.75	75.46	74.85	78.22
Hydrogen production energy efficiency [%]	20.67	10.46	8.99	18.91
Combined cycle efficiency [%]	50.90	48.47	48.33	49.40

4.4.3. Fuel conservation

Figure 6 shows the rate of changes in natural gas consumption savings relative to the evolution of steam-to-biomass ratio in the studied combined cycle using the proposed biomass gasification system. Increasing the amount of hydrogen produced by Reactions R4, R7, and R8 will increase the calorific value of the syngas and make it possible to reduce the share of natural gas.

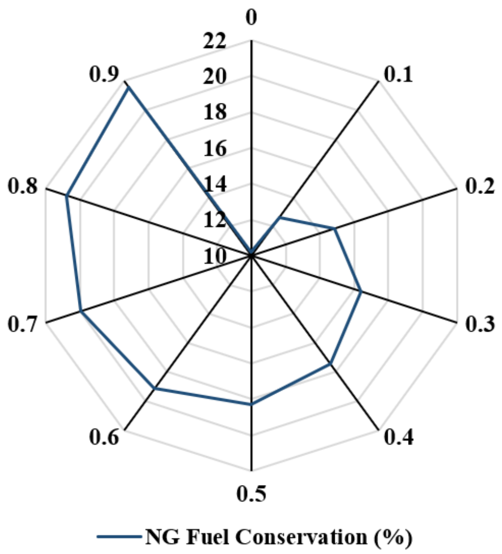

Figure 6. Natural gas fuel conservation relative to steam-to-biomass ratio changes in the proposed combined cycle

Changes in the molar percentage of each component of the synthesized gas due to the variation of the biomass fuel water content entering the system are given in Figure 7. Moisture content increase has a positive effect on the water gasification process, and gas shift reaction in the gasifier and hydrogen content increase is expectable. As can be seen, despite the rise in the amount of moisture in the fuel, the amount of hydrogen in the syngas composition increases; it is not desirable due to the increased production of carbon dioxide. The temperature in the gasifier reactor decreases with fuel moisture content growth. There is some critical point when the temperature at the reactor is too low and the intensity of hydrogen production is down. Therefore, the amount of 10 % humidity can be the acceptable level of biomass bulb content for consumption in this cycle and it will cause, unfavorably, more production of environmental pollutants.

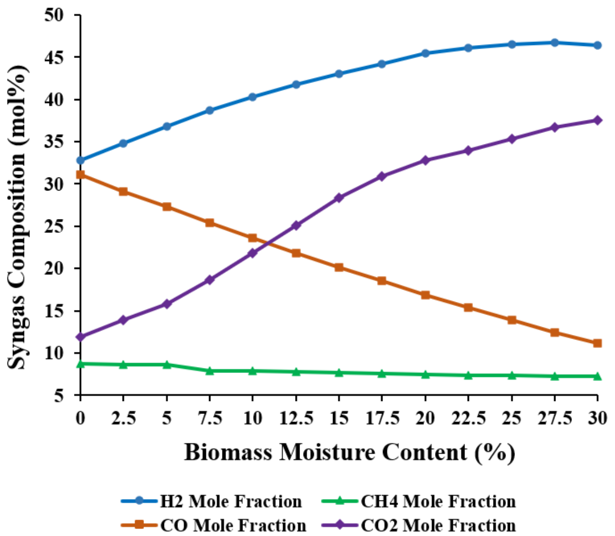

Figure 7. Syngas composition changes relative to biomass moisture variation in the proposed combined cycle

The curve of changes in the syngas components relative to the changes in the equilibrium rate is presented in Figure 8. Based on the results, the equilibrium rate in the range of 0.15 to 0.35 can be acceptable. In this range, the concentrations of major combustible gases, including H_2, CH_4, and CO, are reduced because of oxidation reactions (R1-R3). Higher values lead to a decrease in the share of hydrogen and consequently, reduction of the calorific value of the gas produced. Thus, it is understood that the value considered in this research is a suitable and permissible value according to other parameters affecting the gasification process.

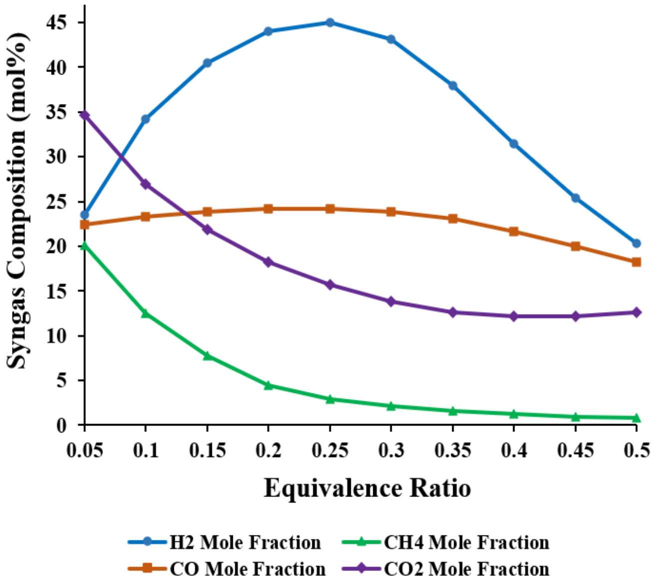

Figure 8. Syngas composition changes relative to equivalence ratio variation in the proposed combined cycle

The effect of the equivalence ratio on lower heating value and cold gas efficiency is presented in Figure 9. As can be seen in the curves of this figure, by increasing the equivalence ratio by more than 0.3, the amount of cold gas efficiency of the gasifier decreases significantly, which is not desirable. Based on what was stated in Section 3, an excessive increase in the amount of air compared to the biomass fuel entering the system will have a negative effect on the production of valuable syngas.

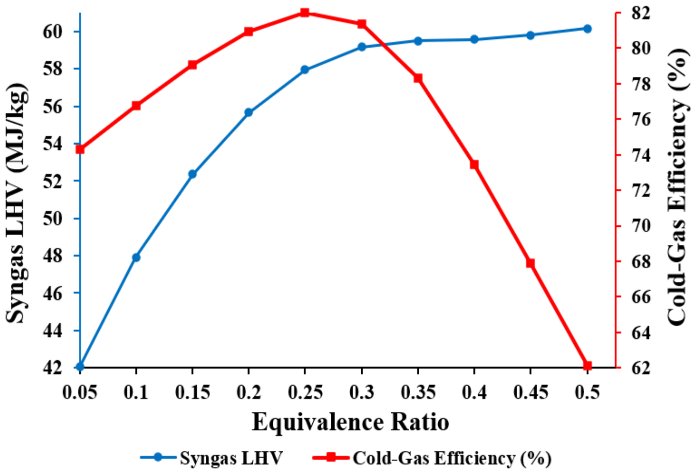

Figure 9. Syngas LHV and gasifier cold gas efficiency changes relative to equivalence ratio variation in the proposed combined cycle

The reduction of the natural gas consumption rate due to the replacement of the syngas in the proposed cycle, compared to the equivalence ratio changes greater than 0.35, is shown in Figure 10. Reducing the amount of syngas production in the gasifier will increase the system's share of natural gas consumption. Therefore, adjusting the cycle fuel system in the declared range for the equivalence ratio is necessary to achieve the goals mentioned in this cycle.

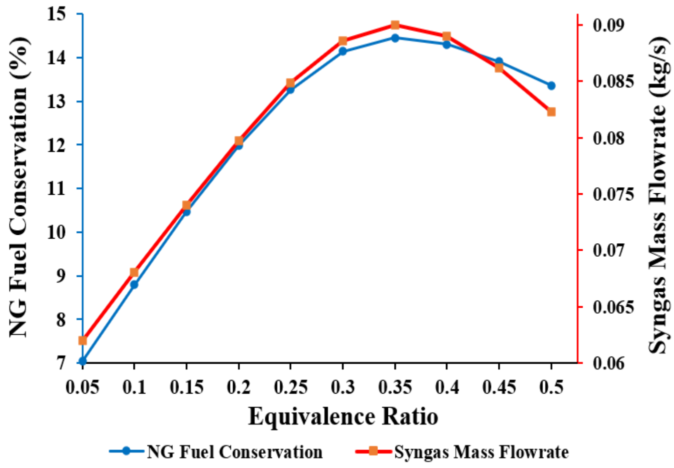

Figure 10. Natural gas consumption and syngas production change relative to equivalence ratio variation in the proposed combined cycle

5. CONCLUSIONS

The present study investigated and analyzed the application of FICFB as an advanced biomass gasification system in a small-scale combined cycle power plant to generate the required fuel fraction. For this purpose, first, thermodynamic study of a combined cycle power plant consisting of two accessible types of gas and steam turbines with nominal capacities of 12.9 and 7 MW was performed. Then, based on the amount of biomass fuel available in Iran, calculations related to the mass and energy balance of the biomass gasifier were fulfilled. The energy modeling results in the proposed power plant indicate that syngas produced by the gasifier could supply about 10 % of the share of fuel consumed.

To increase the competitiveness of the studied cycle, the utilization of a low-temperature cycle to recover the stack heat of the topping combined cycle was proposed. The results demonstrate that the application of the Kalina cycle increased the total efficiency by about 1.7 %.

A parametric study on four biomass fuels of the agricultural type illustrated that wood chips were more desirable in producing syngas with a higher calorific value. Also, parametric analyses were performed on the influential factors of the studied biomass gasifier, and the maximum permissible equivalence ratio was 0.35. In addition, the need to dry the biomass fuel before gasifier feeding and having a maximum of 10 % moisture content were other achievements of this study.

Based on the present study results, gradual elimination of fossil fuels is possible in a step-by-step fashion with renewable energy technologies. Therefore, more steps can be taken for sustainable energy development by adopting a policy of sequential replacement of fossil fuels in regions with adequate biomass fuel capacities.

6. ACKNOWLEDGEMENT

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NOMENCLATURE

C_p	Specific heat capacity (J kg^{-1} K^{-1})
ER	Equivalence ratio

LHV	Lower heating value (kJ kg^{-1})
HHV	Higher heating value (kJ kg^{-1})
$\dot{m}$	Mass (kg)
P	Pressure (bar)
$\dot{Q}$	Heat (W)
S/T	Steam to biomass ratio
T	Temperature (K)
$\dot{W}$	Power (W)

Abbreviations

BC	Bottoming Cycle
CHP	Combined Heat and Power
CGE	Cold Gas Efficiency
FB	Fluidized Bed
FICFB	Fast Internal Circulating Fluidized Bed
GC	Gas Cycle
GT	Gas Turbine
HRSG	Heat Recovery Steam Generator
IBG	Integrated Biomass Gasification
IC	Integrated Cycle
ORC	Organic Rankine Cycle
ST	Steam Turbine

Greek letters

η	Efficiency

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