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Comparison of Combustion and Gasification for Energy Recovery from Residual Woody Biomass

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ABSTRACT

More than half of global electrical and thermal energy is generated by fossil fuels, around 63% in 2019. This is one of the main causes of greenhouse gas (GHG) emissions, responsible for the increase of the atmospheric average temperature above the reference level. Combined heat and power (CHP) generation from biomass may contribute to increasing renewable energy generation and reducing GHGs emissions, pursuing the goals of the European Union green deal 2021. In the present study, CHP generation potentiality, efficiencies, and environmental impact are compared numerically by using Aspen Plus V8.8 software between the thermal treatment of combustion and gasification integrated with a gas turbine system of residual woody biomass. The gas turbine is powered by the exhausts of biomass combustion in the first configuration, and by the exhausts of syngas combustion in the second one. Modeling of cogeneration through biomass combustion and gasification is developed based on the available literature data, founding a good agreement with the experimental campaign. Wood combustion is more advantageous in terms of cogeneration efficiencies (around 40% higher), whereas gasification emits lower GHGs.

1. INTRODUCTION

Fossil fuels (petroleum, coal, and natural gas) have significantly contributed to global primary energy demand and the quantity is 80-85% [1, 2] whereas the share is 63.14% for electricity generation in 2019 [3]. Energy generation from fossil fuels is one of the main reasons for the continuous increase in CO_2 concentration in the atmosphere [4]. CO_2 has the highest contribution to greenhouse gases (GHGs) (74.4%) followed by CH_4 (17.3%) with a minor fraction due to the remaining components of CO, SOx, NOx, HCl, acetate, mercury, dioxins, furan, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons [5, 6]. Such GHGs are recognized as responsible for the global average temperature increase above the reference level, with an increment of 0.62°C in the period from 1990 to 2019 [7]. Increasing the production of renewable energy would reduce the dependency on fossil fuels and consequently the rise in global average temperature [5, 7, 8]. In 2021, the European Union (EU) announced the green deal to encourage the member states to reduce their dependency on fossil fuels and the consequent environmental pollution by setting different targets to be reached by 2030, including:

- the increase in renewable energy generation to support 40% of primary energy demand;
- the reduction of GHGs emissions by 55% compared to the 1990 level [9].

In this context, the conversion of biomass to combined heat and power (CHP) offers two simultaneous advantages: the increase in renewable energy generation with the consequent reduction of GHGs emissions and the decrease of residual material to be disposed of. Developing a sustainable conversion technique of biomass to CHP with high efficiency is a challenging issue for the scientific community, considering that such electrical efficiency is on average lower than 20% [10].

Numerical analysis for the optimization of operating parameters involved in the cogeneration process from biomass with maximum process performances can save time and economic costs if compared to performing an experimental campaign [11, 12]. For this reason, numerical modelling is commonly employed to predict the performance of systems aimed at energy recovery from biomass. A system integrating wood combustion and power generation through a gas turbine has been analyzed by Wiranarongkorn et al. [13], through a model developed in Aspen Plus. By using such a model authors predicted an electrical efficiency of 14.5%. By considering a similar layout of biomass combustion, Marseglia et al. [14] estimated an electrical efficiency of 13.15% for CHP from residual wood blends (mixture of 70 wt.% maritime pine and 30 wt.% cypress). Also, biomass gasification combined with a gas turbine for power generation has been investigated by several researchers. Machin et al. [15] considered the thermal treatment of sugarcane bagasse in a bubbling fluidized bed gasifier finding an electrical efficiency of 12.9%, whereas Pedroso et al. [16] estimated an electrical efficiency of 14.7% by considering an entrained flow gasifier.

The selection of a thermal treatment process for energy recovery from biomass depends on the energy efficiency and emissions profiles. The comparison between biomass combustion and gasification process in terms of energy and environmental performance is not extensively studied in the literature. Briones-Hidrovo et al. [17] analyzed combustion and gasification process performances in terms of energy return on an energy investment basis and life cycle assessment, founding that gasification is better from an environmental point of view whereas combustion has a higher energy performance. Parascanu et al. [18] observed that gasification is advantageous compared to combustion for electricity generation. They assessed two biomass sources (sugarcane and agave bagasse) in terms of environmental impacts of ozone depletion, terrestrial acidification, fossil fuels, and human toxicity potential. Mdhluli and Harding [19] reported that electricity generation through gasification integrated with a gas turbine from biomass residues (maize cobs, maize stover, or wheat stalks) creates 90% less air, water, and soil pollution over the depletion of land, ozone layer, and fossil fuel compared to coal combustion plants.

This study aims at comparing energy recovery from residual wood (a mixture of 70 wt.% maritime pine and 30 wt.% cypress) by considering the thermal treatments of combustion and gasification coupled with a gas turbine for CHP generation, in terms of energy efficiency and emissions. To the best of authors' knowledge, such a study is proposed here for the first time. The numerical analysis is performed by using Aspen Plus V8.8 software (Bedford, Massachusetts, USA). The model of CHP through combustion and gasification is developed considering experimental data available in the literature. It is used to assess the efficiency of the processes as well as their environmental impact, in terms of emissions.

2. METHODOLOGY

A schematic view of the two layouts analysed in the present study is presented in Figure 1. Figure 1(a) shows the configuration with wood combustion (WC-GT from now on), whereas Figure 1(b) illustrates the layout based on gasification (WG-GT from now on).

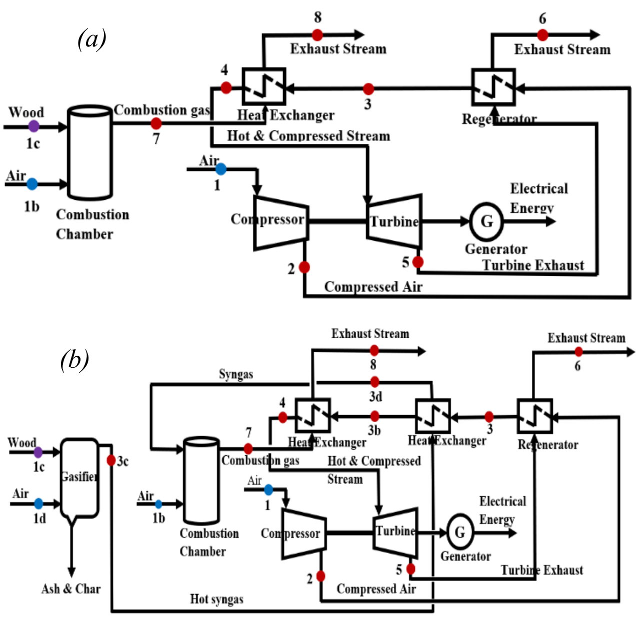

Figure 1. Schematic view of proposed plant for the conversion of wood to CHP through (a) WC-GT and (b) WG-GT configurations

The model is developed by connecting different unit operation blocks available in the Aspen Plus library. The functional activities of each unit operation block used to assess the proposed plant are presented in Table 1.

Table 1. Functional description of different unit operation blocks used in the developed Aspen Plus flowsheet

Process	Block name	Function
Combustion and Gasification	RYield	It decomposes wood residues into conventional (C, H_2, N_2, S, H_2O, and O_2) and non-conventional (ash) components based on ultimate elemental analysis applied through an external Fortran subroutine in a calculator [12].
	Separator	It separates conventional and nonconventional components.
	RGibbs	It completes the combustion or gasification reactions of conventional components present in residual wood by minimizing Gibbs free energy.
	Heater	It heats the incoming air to reach gasification temperature.
	Heater	It heats the ash stream to equalize the temperature with that of combustion or gasification products.
	Mixer	It mixes the combustion or gasification products and ash to make a homogeneous stream like a combustion or gasification plant.
	SSplit	It separates ash and char from combustion products or syngas.
	Heat exchanger	It cools down the syngas before its use as fuel in a combustor by exchanging heat with the turbine exit stream.
	RGibbs	It completes the combustion of syngas by minimizing Gibbs free energy.
Gas Turbine	Compressor	It increases the incoming air pressure through isentropic compression.
	Regenerator	It raises the compressed air temperature by recovering heat from the turbine exit stream.
	Heat exchanger	It increases the temperature of the stream exiting the regenerator through heat exchange with the combustion products.
	Turbine	It converts the thermal energy of the exhausts to mechanical energy that is used to run a generator to produce electricity.
	Heater	It recovers thermal energy from the streams exiting the heat exchanger and the regenerator.

2.1 Model development

Several assumptions are taken into account to simulate CHP generation from residual wood through combustion and gasification [11, 12, 14]:

- The models are zero-dimensional;
- Decomposition of residual wood is completed instantaneously;
- Combustion and gasification reactions reach equilibrium with steady-state conditions;
- Hydrodynamic characteristics of combustion and gasification chamber are neglected;

- Char generated during gasification of wood residues is full of carbon;
- Combustion and gasification are completed at the isothermal condition;
- Gaseous products generated during combustion and gasification of wood residues show ideal behavior;
- Combustion and gasification are completed at atmospheric pressure;
- Tar formation during wood residue gasification is not counted as the researchers do not consider it during the biomass gasification model. Tar formation neglect does not have any effect on energy potentiality and environmental impact analysis which are the main aim of the present study [20-22].

The reactions considered in the model development of combustion and gasification together with the heat of reaction (ΔH) [12] are presented in Table 2.

Table 2. List of chemical reactions considered during wood residue combustion and gasification process simulation with the heat of reaction [12]

Reaction No.	Reaction scheme	Reaction name	ΔH, (KJ/mol)
R1	$N_2 + O_2 \rightarrow 2NO$	Nitric oxide formation	+90.2
R2	$N_2 + 2O_2 \rightarrow 2NO_2$	Nitrogen dioxide formation	+36.9
R3	$C + H_2O \rightarrow H_2 + CO$	Water gas	+131.0
R4	$C + O_2 \rightarrow CO_2$	Carbon combustion	-393.0
R5	$C + 2H_2 \rightarrow CH_4$	Methanation	-74.0
R6	$CO + H_2O \rightarrow H_2 + CO_2$	Water Gas Shift	-41.0
R7	$C_2H_4 + 3O_2 \rightarrow 2H_2O + 2CO_2$	Ethene combustion	-964.0
R8	$2H_2 + O_2 \rightarrow 2H_2O$	Hydrogen combustion	-242.0

Reactions R1, R2, R4, and R8 are considered to model combustion, whereas reactions from R3 to R8 regard gasification modeling.

Gasification reactions do not reach equilibrium at unique gasification temperatures as the kinetic constant of each reaction highly depends on temperature [23]. Consequently, syngas composition predicted through the developed model differs from the experimental campaign, reducing the accuracy of the model [11]. According to the available literature, the deviation between the simulation results and experimental outcomes should be lower than ± 20% to have a reliable model [11, 12]. This condition can be ensured by assigning a specific temperature at each gasification reaction to restrict the equilibrium position, as expressed in the Eq. (1):

$$T_{Eqlm} = T_{Gasf} + \Delta T_{Appr} \quad (1)$$

where, T_{Eqlm} is the equilibrium temperature, T_{Gasf} is the gasification temperature and ΔT_{Appr} is a specific value of temperature to which the gasification reaction is restricted.

The energy content of syngas generated through the gasification of residual wood is assessed by considering its lower heating value (LHV), calculated according to Eq. (2) [20]:

$$LHV_{syng}\ (MJ/Nm^3) = 0.108y_{H_2} + 0.126y_{CO} + 0.358y_{CH_4} \quad (2)$$

where, y_{H_2}, y_{CO}, and y_{CH_4} represent the fraction of H_2, CO, and CH_4 by volume respectively, present in syngas.

Finally, regarding the simulation of the gas turbine, the system is simulated by considering a compressor and a turbine whose inputs are isentropic and mechanical efficiencies and pressure ratio.

2.2 Assessment of process performances

The two developed layouts of WC-GT and WG-GT configurations are compared in terms of energy performance and emissions to the atmosphere. Energy performance is evaluated through electrical (η_{el}), thermal (η_{th}) and system (η_{sys}) efficiencies corresponding to Eqns. (3) to (5).

$$\eta_{el}\ (\%) = \frac{\dot{N}_{TURB}}{LHV_{wood} \cdot \dot{m}_{wood}} \cdot 100 \quad (3)$$

$$\eta_{th}\ (\%) = \frac{\dot{Q}_{REG} + \dot{Q}_{HEX} + \dot{Q}_{SYNG,COOL}}{LHV_{wood} \cdot \dot{m}_{wood}} \cdot 100 \quad (4)$$

$$\eta_{sys}\ (\%) = \frac{\dot{N}_{TURB} + \dot{Q}_{REG} + \dot{Q}_{HEX}}{LHV_{wood} \cdot \dot{m}_{wood}} \cdot 100 \quad (5)$$

where, $\dot{N}_{TURB}$ denotes the effective power obtained from the turbine, $\dot{Q}_{REG}$ represents the thermal power available from the regenerator exhausts, $\dot{Q}_{HEX}$ is the thermal power that can be recovered by cooling the exhausts of wood residues or syngas combustion, $\dot{Q}_{SYNG,COOL}$ is the thermal power available from syngas cooling. The available thermal power is determined for all the heat exchangers by considering a usable temperature of 80°C [11]. LHV_{wood} and $\dot{m}_{wood}$ stand for LHV and mass flow rate of wood residues respectively.

As commonly proposed in the literature, the gasification process performance is also assessed through cold gas efficiency (CGE) and carbon conversion efficiency (CCE). CGE expresses the ratio between the energy content exiting the gasifier as syngas and that of the biomass fed to the reactor. CCE represents the fractional movement of carbon content from the fed (residual wood) to the product phase (syngas) [11, 12].

2.3 Data acquisition for combustion and gasification model development

Data from the available literature is used for calibration and validation of combustion and gasification models [14, 24].

More in detail, the model developed to simulate combustion is calibrated by using the outcomes of an experimental campaign carried out on a lab-scale system [14]. The results of this experimental campaign are also used to calibrate the gas turbine model. Beyond ultimate and proximate analyses of the biomass, the input data reported in Table 3 are used to develop the model. After calibration, the model is used to derive the mass flow rate of the combustion exhausts, the temperature and flow rates of the flow streams, the net available power of the turbine, and the total energy efficiency of the system.

Table 3. Input data used for calibration of wood residue combustion model [14]

Stream	*Property
Biomass	Mass flow rate: 179 kg/h Temperature, T_{1c}: 20.0°C Pressure: 1.00 bar
Air entering the combustor	Mass flow rate: 1800 kg/h Temperature, T_1: 20.0°C Pressure: 1.00 bar
Air entering the compressor	Mass flow rate: 2845 kg/h
Compressed air	Temperature, T_2: 224°C
Air exiting the regenerator	Temperature, T_3: 411°C
Hot combustion exhaust gas	Temperature, T_7: 1020°C
Cold combustion exhaust gas	Temperature, T_8: 414°C

*Numbering related to the position shown in Figure 1 (a).

Regarding gasification, data available in the literature related to bamboo chips are considered for calibration and validation of the model. Indeed, such a substrate is similar to residual wood considered in the present work, in terms of proximate and ultimate analysis. Proximate and ultimate analysis with LHV of residual wood and bamboo chips are presented in Table 4.

Table 4. Properties of wood and bamboo chips with LHV on a dry basis [14, 24]

Properties	Wood residues	Bamboo chips
Proximate analysis (wt.%)		
Moisture content	7.84	7.14
Volatile matter	77.19	80.06
Fixed caron	22.79	18.33
Ash content	0.026	1.61
Ultimate analysis (wt.%)		
C	47.10	44.83
H	6.10	5.96
N	-	0.35
S	-	0.15
O	47.78	47.10
LHV (MJ/kg ds)	17.74	18.32

ds = Dry solid

Table 5. Overview of gasification conditions and syngas properties data for gasification process simulation

Test conditions	I	II	III	IV
Temperature (°C)	800			
ER	0.2	0.3	0.4	0.5
Fed flow rate (kg/h)	1.0			
Syngas composition, vol.% (dry & N_2 free basis)				
H_2	16.96	11.74	7.18	3.48
CO	24.13	18.70	11.30	6.96
CO_2	56.31	68.70	81.30	88.70
CH_4	3.26	1.74	1.31	0.85

The different operating conditions and the corresponding syngas compositions considered to calibrate and validate the gasification model are collected from the literature and summarized in Table 5 [24]. The gasification model is calibrated based on the experimental condition I, by setting a 5% standard deviation between the syngas composition obtained through the numerical simulation and the experimental one. This allows to identify ΔT_{Appr} of each gasification reaction. Experimental data at conditions II to IV are used for validation.

Also, working conditions to simulate the gas turbine are collected from the literature: the pressure ratio in the compressor is 4.5 and in the turbine is 0.22 [14].

3. RESULTS AND DISCUSSIONS

3.1 Combustion model calibration and validation

As mentioned above, the combustion model is calibrated by applying the operating data presented in Table 3. The predicted outcomes are presented in Table 6 with the deviation from experimental data [14] at different points of the process (the numbering refers to the position stated in Figure 1(a)). The comparison shows a good agreement between numerical and experimental data.

Table 6. Experimental and numerical values comparison (the numbering refers to Figure 1(a)) [14]

Stream	Experimental Value	Numerical Value	Deviation (%)
Air entering the turbine	Temperature, T_4: 866°C	Temperature, T_4: 872°C	0.69
Air exiting the turbine	Temperature, T_5: 586°C	Temperature, T_5: 560°C	4.43
Air exiting the regenerator	Temperature, T_6: 399°C	Temperature, T_6: 378°C	5.26
Electrical efficiency	13.2%	12.3%	6.82

3.2 Gasification model calibration and validation

The limiting temperature predicted to restrict gasification reactions (illustrated in Table 2) is presented in Table 7.

Table 7. Predicted limiting temperature to restrict equilibrium of gasification reaction

Reaction NO.	ΔT_{Appr} (°C)
R3	-276.8
R4	-49.5
R5	-379.1
R6	381.4
R7	52.8
R8	35.9

The estimated quantity of carbon from bamboo chips that reacts to form syngas is 75.8%.

The difference between the syngas composition and LHV predicted through the developed model and the experimental data during calibration and validation is presented in Figure 2.

The developed model has a good agreement with the experimental results as the average deviation of syngas composition and LHV from experimental data varies between 3 and 10.2%. Syngas LHV is overpredicted due to the overprediction of H_2 and CO as these two constituents significantly affect LHV [12, 20].

Residual wood is converted to syngas by considering a gasification temperature of 800°C (similar to the model validation condition) and an ER of 0.35. This ER allows reducing the tar concentration to increase gas turbine performance and lifetime [11, 12]. The properties of generated syngas used to power the gas turbine with gasification process performances are presented in Table 8. Gasification process performance is assessed through syngas LHV, CGE, and CCE.

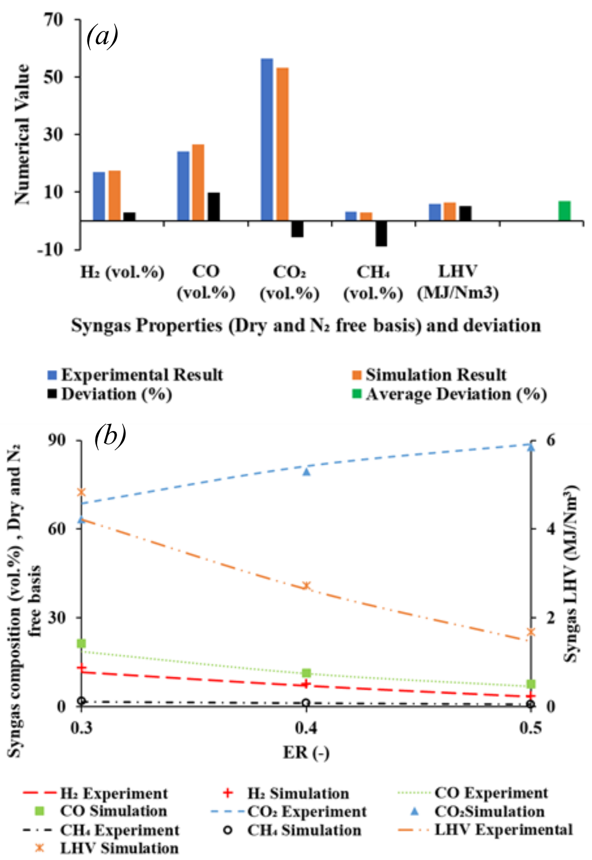

Figure 2. Difference between the results predicted through the developed model and the experimental outcomes during model calibration (a) and validation (b)

Table 8. Syngas composition and gasification process performances used in WG-GT configuration

Syngas properties		Gasification performances	
Components	Composition, vol% (dry & N_2 free basis)		
H_2	14.80	LHV (MJ/Nm³)	5.10
CO	24.23		
CO_2	54.21	CGE (%)	27.11
CH_4	1.22		
C_2H_4	5.53	CCE (%)	52.11

By considering the same turbine size of WC-GT in WG-GT the electrical (2.89%) and thermal (13.84%) efficiencies are significantly low, due to the lower mass flow rate of exhausts available for power production. Thus a sensitivity analysis is performed by varying the incoming airflow rate from 1422 to 2845 kg/h to identify the value that maximizes the electrical efficiency. The highest electrical (7.42%) and thermal (31.48%) efficiencies are found for an airflow rate of 2096 kg/h which is around 73.7% of WC-GT configuration.

3.3 Cogeneration process performances

A comparison of temperatures at different positions between WC-GT and WG-GT configurations shown in Figure 1 is presented in Table 9. For WG-GT, the airflow rate identified through the sensitivity analysis is considered.

Table 9. Comparison of predicted temperatures for WC-GT and WG-GT configurations

Positions	WC-GT	WG-GT
1	20	20
1b	20	20
1c	20	20
1d	-	20
2	224	222
3	411	474
3b	-	570
3c	-	800
3d	-	353
4	872	765
5	560	479
6	378	227
7	1020	1020
8	414	575
9	80	80

The results related to cogeneration efficiencies, electrical and thermal energy generation potentiality, and emission profiles of the two proposed layouts are presented in Table 10.

Table 10. Cogeneration efficiencies and CHP generation potentiality of wood residues and emission profile

Layout		WC-GT	WG-GT
Energy generation efficiency (%)	η_{el}	12.32	7.42
	η_{th}	50.33	31.48
	η_{sys}	62.65	38.89
Energy generation potentiality (kW/kg as DS)	Electrical	0.61	2.48
	Thermal	0.37	1.55
Emission profiles (kg/kWh_{el})	CO_2	2.69	2.80
	NOx	0.0014	0.0050

As clearly shown in Table 10, the WC-GT configuration has a higher energy generation efficiency compared to the WG-GT scheme, due to the higher operating temperatures. Obviously, due to the lower size of the gas turbine, by considering the same primary energy, the energy generation potentiality of WC-GT is higher. However, WG-GT appears to be more convenient in terms of environmental impact: indeed the CO_2 emission is similar whereas that of NOx is significantly lower. This is due to the lower operating temperature for the oxygen deficit environment in the gasifier [25].

4. CONCLUSION

Conversion of energy content present in residual wood to combine heat and power through two distinct treatment schemes is numerically analyzed to compare the energy generation efficiency and emission to the environment. More in detail, thermal treatments of combustion and gasification coupled to a gas turbine are compared. The wood combustion and gasification model are calibrated and validated based on the experimental data available in the literature, founding a good agreement as the deviation varies in the range of 0.7 – 6.8% and 3.0 – 10.2%, respectively. Due to the lower mass flow rate of exhausts available for power production in the layout based on wood gasification, the turbine size is lower than that used in the scheme with combustion. Despite a sensitivity analysed being performed to identify the turbine size that maximizes the electrical efficiency for the layout of wood gasification, combustion presents higher cogeneration efficiencies. However, gasification offers more benefits from an environmental point of view since the CO_2 emission is almost similar whereas that of NOx is significantly lower.

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NOMENCLATURE

LHV_{syng}	Syngas lower heating value, MJ/Nm^3
LHV_{Wood}	Lower heating value of wood, MJ/kg
$\dot{m}_{wood}$	Mass flow rate of wood, kg/h
$\dot{N}_{TURB}$	Electrical power, kW
$\dot{Q}_{HEX}$	Thermal power from heat exchanger, kW
$\dot{Q}_{REG}$	Thermal power from the regenerator, kW
$\dot{Q}_{SYNG,COOL}$	Thermal power from syngas cooling, kW
T_{Eqlm}	Equilibrium temperature, ℃
T_{Gasf}	Gasification temperature, ℃
y_{H_2}	Volume fraction of H_2 in syngas, %
y_{CO}	Volume fraction of CO in syngas, %
y_{CH_4}	Volume fraction of CH_4 in syngas, %
ΔH	Heat of reaction, KJ/mol
ΔT_{Appr}	Limit of gasifier temperature, ℃

Greek symbols

η_{el}	Electrical efficiency, %
η_{sys}	Cogeneration system efficiency, %
η_{th}	Thermal efficiency, %

Subscripts

Appr	Approach
el	Electrical
Eqlm	Equilibrium
Gasf	Gasification
syng	syngas
sys	System
th	Thermal
Wood	Wood