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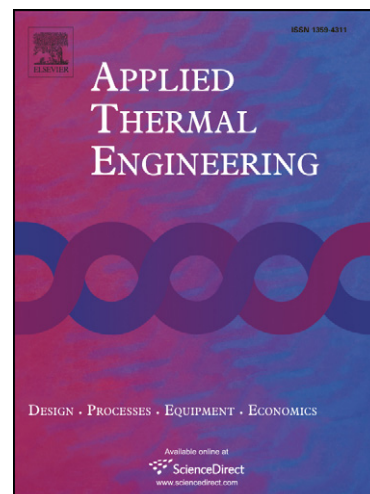
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THE USE OF BIOMASS SYNGAS IN IC ENGINES AND CCGT PLANTS: A COMPARATIVE ANALYSIS

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ABSTRACT

This paper studies the use of biomass syngas, obtained from pyrolysis or gasification, in traditional energy-production systems, specifically Internal Combustion (IC) engines and Combined Cycle Gas Turbine (CCGT) plants. The biomass conversion stage has been simulated by means of a gas-solid thermodynamic model. The IC and CCGT plant configurations were optimised to maximise heat and power production. Several types of biomass feedstock were studied to assess their potential for energy production and their effect on the environment. This system was also compared with the coupling between biomass gasification and fuel cells.

Keywords: biomass; gasification; IC engine; CCGT.

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1. Introduction

Biomass has recently received considerable attention as a potential substitute for fossil fuels in heat and power generation, as it allows for a reduction in environmental impact as well as offering an interesting solution to waste disposal.

On the other hand, in open literature it is possible to find several works on the innovative coupling between biomass gasification and fuel cells [1-9], whereas works on the coupling with traditional power generators, such as IC engines and gas turbines, are relatively scarce [10-17].

The coupling of biomass conversion with more traditional power generators could be an easier way to gain, in the early stages, greater market-diffusion.

For this reason, in this paper, different plant solutions have been studied using internal combustion gas engines and combined cycle gas turbine plants. The configurations have been optimised in order to maximise heat and power production, while the process analysis has been performed by simulating the system performances with appropriate codes.

Several types of biomass have been considered as feedstock (bagasse; pine sawdust; poplar sawdust; almond shells) and the energy and environmental balance has been evaluated in each case studied.

Finally, the results obtained have been discussed in relation to the previous results on

fuel cell systems.

2. Reference plant layouts

Two reference plants were studied; both producing biomass syngas with a CFB (Circulating Fluidised-Bed) gasifier.

In the first layout the syngas obtained from gasification was used in an IC (Internal Combustion) gas engine, in the second layout the syngas was used in a CCGT (Combined Cycle Gas Turbine) plant.

A general description of the layouts tested is given below; the plant components and their simulation approach will be discussed in the subsequent chapters.

2.1 Layout 1: IC gas engine power generator

Figure 1 shows the first plant configuration. It represents a simple syngas utilisation in an IC engine. The syngas at the outlet the gasifier is piped through a clean-up section to the engine to produce electric energy. The flue gas from the burner coupled to the gasifier and the exhaust gas from the engine are also subjected to a clean-up process and then piped to the chimney. All the plant stages operate at atmospheric pressure. In order to optimise the Combined Heat and Power (CHP) production, thermal energy is recovered from the syngas stream, before the clean-up module, and from the burner flue gas stream (in the air pre-heating device and in the heat exchanger with the

cleaned-up combustion products).

2.2 Layout 2: CCGT combined cycle gas turbine power generator

In the second plant layout (Figure 2) the syngas is piped through a clean-up module into the power generation section consisting of a CCGT. The syngas is compressed and injected into the gas turbine combustion chamber where it gets burned after mixing with air with a high ER value (3.35). Except for the gas turbine engine and the steam cycle, all the plant stages operate at atmospheric pressure.

Since the exhaust gas from the turbine has a high oxygen content, part of the exhaust gas flow is piped to the gasifier burner, as oxidant agent, and part is mixed with the flue gas at the burner outlet. The flue gas, then, undergoes a clean-up process before exiting the plant.

Since such output stream is characterised by a significant high-temperature flue-gas flow, it seems reasonable to exploit it to generate water steam by means of a Heat Recovery Steam Generator (HRSG) and supply it to a steam turbine. This configuration is usually called an IGCC (Integrated Gasification Combined Cycle).

3. Syngas production section

The syngas production section is represented by a CFB system consisting of a gasifier heated by a burner [1].

The biomass thermochemical conversion in the gasifier is carried out without oxidant (pyrolysis) or using steam (steam gasification).

The output products are the syngas, the solid phase (char) and the liquid phase (tar).

The process is endothermic and the heat necessary to sustain the reactions is supplied by the coupled burner in which the carbon-based char is oxidised with auxiliary fuel, if necessary. The thermal exchange between the two modules occurs through a fluidised sand-bed.

The syngas obtained is piped through a clean-up section to the utilisation stage.

The burner temperature, in our study assumed equal to 900°C, should be monitored, in the actual plant, with appropriate sensors in order to assess the correct amount of auxiliary fuel needed to keep such temperature constant. The system should include a safety valve to discharge the excess gas in case the quantity of char causes the temperature to rise above the desired value.

For the thermochemical conversion process, several types of biomass have been considered as feedstock; it should be noted that when using this configuration it is advisable to grind the biomass into small chips in order to maximise the specific contact surface between the solid and the gas phase.

4. Clean-up section

The presence of by-products in the syngas makes it necessary to clean the gaseous flow before its use by the power generation section. Moreover, the exhaust/flue gases have a higher pollutant level and also have to be purified before being piped to the chimney in order to reach the desired standards.

4.1 Syngas quality requirements

IC gas engines are more tolerant of contaminants than gas turbines [18-21]. In particular, it is possible to have a tar content up to 50-100 mg Nm⁻³ in the produced gas.

However, in the literature there are very few reliable data on the gas quality specifications requirements and only some of those are taken from the operating values of real plants.

Alkali (particularly Na and K in the biomass ashes) and sulfur compounds, which corrode the blades, have the most deleterious effects on gas turbines. Particulate matter (solid inerts such as char, ash and sand from the gasifier bed) also has a damaging effect on any moving parts.

The tar condensable phase is partly deposited in the piping system (causing fouling of heat exchangers) and it is a potential problem if the syngas has to be compressed, as it

will deposit in the compressor. However turbines are not very sensitive to tar, as the gas temperature is usually high and tars are in vapour form.

Chloride compounds interact with several metals at the temperatures used and this effect is worsened by the change from reducing (gasifier) to oxidising (gas turbine combustion chamber) environments.

Even if the gas quality requirements are very strict, the gas characteristics given in the literature should be considered with caution, since, for example, the type of engine used has to be taken into account and good engine operation can also be reached with higher pollutant values (e.g. tars) than the limits available in the literature [22].

Moreover, several methods of pollutant sampling and analysis procedure are in use and they may sometimes produce results that cannot be directly compared (e.g. [23], [24]).

4.2 Clean-up systems

In this study, a conventional gas purification arrangement for a biomass plant [25] has been adopted for the syngas and the flue or exhaust-gas clean-up, including the following stages: cyclone, bag filter, scrubber. The process parameters assumed for the clean-up section are reported in Table 1.

For the considered plant configurations all the clean-up treatment stages are characterised by a pressure of 1 bar as the thermal conversion process is conducted at atmospheric pressure.

The balance of plant has been optimised in order to maximise CHP production, so the incoming gas flowing to the clean-up module is cooled in counter-current heat exchangers at a temperature of about 120-150°C, by means of a colder stream in the different plant stages:

- the steam generation stage (for the gasification process) and a heat recovery stage on the syngas stream (layouts 1 and 2);
- the heating stage of the flue gas (in a heat exchanger between dirty and clean combustion products) in order to reach the desirable temperature at the chimney (layouts 1 and 2);
- the heat recovery steam generator that feeds the steam cycle in layout 2;
- the pre-heating stage of the air piped to the burner (layouts 1 and 2).

After the cooling stage, the gas passes through the cyclone, capable of removing particulate matter of a diameter greater than approximately 5 μm , and through the bag filter, which has a high removal efficiency for a wide range of granulometries.

The gas is then treated with a scrubber, which reduces its temperature to less than 100°C: this purification process favours steam condensation and the removal of the

sulfur and halogenous compounds, so increasing the reliability of the power generator [25].

Finally, the outlet stream, which has a temperature of about 30°C (adiabatic saturation temperature), is then piped to the engine inlet or compressed to the gas turbine operative pressures. It seems reasonable to use this conventional wet cleaning system for the syngas treatment because gas engines are generally fuelled with cold gas and the dew point of the producer gas is generally higher than the gas inlet temperature and hence a condensate will be generated in all gas cleaning systems.

5. Syngas utilisation sections

In the first plant layout the syngas stream feeds an internal combustion gas engine (conventional reciprocating Otto cycle); the inlet syngas is at ambient temperature (approximately 30°C), since it comes from the wet clean-up stage.

The thermal and electrical efficiencies have been assumed respectively at 35% and 40% and a value of 150°C has been chosen for the exhaust gas temperature: these values are in agreement with real-life engine performances [26] and are compatible with gas engines whose size ranges from 0.5 to 3 MW total output (8 to 24 cylinders and 17 to 125 liters total displacement, respectively), fed by gasification syngas, biogas, landfill gas, coal mine gas and sewage gas. The assumptions for the thermal efficiency

value and the exhaust temperature also establish the recoverable thermal energy fraction.

Table 2 shows the parameters adopted for the first plant layout.

In the second plant layout, the power generation stage is represented by a gas turbine engine with a combined steam cycle. The process parameters are shown in Table 3 and discussed here for the reference case of pine sawdust feeding. The adoption of advanced technologies for IGCC plants (i.e. Integrated Gasification Combined Cycle) are reasonable for capacities from 400 up to 600 MW range, that are characterized by an overall efficiency of 45-50% [26].

The gas turbine engine is fed with syngas at ambient temperature (30°C) that is compressed up to 10 bar pressure before entering the combustion chamber, where it gets burned at a temperature of approximately 1190°C.

After the expansion in the turbine, the exhaust gas (at 640°C) is partly exploited as comburent agent in the CFB burner and partly (mixed with the exiting burner flue gas) in a heat recovery steam generator HRSG in order to produce steam that feeds a steam turbine.

The HRSG has been assumed to be a single-pressure stage and consists of three different heat exchangers working in series:

- economiser: in which the liquid water is pumped (to 40 bar) and preheated to

the vaporisation temperature (250°C);

- evaporator: where water vaporisation is carried out (250°C, 40 bar);
- super-heater: in which superheated steam is produced (410-490°C, 40 bar).

The energy recovered from the flue gas causes its temperature to decrease from 700 to 220°C between the inlet and outlet sections of the HRSG.

6. Simulation tools

The syngas production section has been modelled with a chemical reaction equilibrium approach. A code written in Matlab environment has been developed for this purpose [27] using the Cantera software library (a collection of object-oriented software tools for problems involving chemical kinetics, thermodynamics, and transport processes [28]). The solver implemented in Cantera is a version of the Villars-Cruise-Smith (VCS) algorithm (a method well suited to handling multiphase problems), which finds the composition minimising the total Gibbs free energy of an ideal mixture [29]. The NASA [30] and the GRI-MECH [31] databases have been used to evaluate the thermodynamic properties of the chemical species considered in the model. To estimate the yield of both the gaseous and solid phases, an improved two-phase formulation of the model has been used. The considered reaction product pool consists of 61 chemical species, 60 for the gaseous phase and 1 (allotropic form of carbon graphite) for the solid one. The chosen compounds are related to the C, H, O, N and S

elements usually present in the biomass. The calculated yield of solid carbon can be used as a rough estimate of the actual charcoal residue of the thermal conversion process.

NASA polynomials implemented in Cantera have also been used to calculate the thermodynamic properties of the cycle fluids (gas and water steam). For example, this allowed the CCGT power generator behaviour to be evaluated considering a Brayton-Joule cycle and a Rankine cycle with superheated steam.

The balance of each plant considered has been carried out by supplementing the thermodynamic analysis of the reacting stages (gasifier, burner, etc.) with an evaluation of the energy fluxes arising from the other plant components needed for the actual operation (generator, clean-up, heat exchangers, etc.). The integration of the developed models has been performed in the Matlab environment, using the Simulink object-oriented language. In this kind of simulation, each plant stage is represented by an object that interacts with the others and contains a code (called the *s-function*), which is a subroutine of the main program (i.e. the whole system). Figure 3 shows a typical Simulink environment.

The previous sketch, chosen as an example, represents the CFB stage of the second plant layout (i.e. the gasification stage), whose s-function consists of the developed

chemical equilibrium model, taking as input the biomass and the gasifying agent and giving as output the syngas and the char yields, has been highlighted.

7. Mass balance and product characterisation

Several types of biomass have been used as feedstock: bagasse; pine sawdust; poplar sawdust; almond shells (Table 4).

All the biomasses considered consist of industrial, agricultural and forest waste that is readily available on the market.

The steam to carbon ratio (SC) and the gasification temperature that optimise the biomass thermal conversion process have been calculated.

Figure 4 presents the gaseous and the solid fractions as a function of SC for the bagasse.

As expected, the production of solid carbon is a decreasing function of the SC parameter, since, as the quantity of the oxidant increases, the residual solid matter is subjected to a more efficient gasification process.

The equilibrium simulations show that the proper SC value is sometimes reached using the water fraction found in the biomass alone (layout 2), so that the combustion of the produced char allows the process to be autothermal (see Table 5). In fact, if the char fraction is not enough, an auxiliary fuel must be burned in the furnace, causing a decline in the global efficiency in spite of the increased syngas-production efficiency.

The gasifier temperature, optimised in order to produce the right char fraction to achieve maximum plant efficiency (the results of the optimisation procedure are shown for the IC gas engine plant in Figure 5), is also different for each feedstock considered, as shown in Table 5 (the ultimate analysis of the feeding materials is shown in Table 4). Table 6 shows the molar fraction composition of the syngas, calculated for each feedstock. As already stated, no gasifying agent was used in the second layout studied (so that biomass is pyrolysed), while in the first layout an SC value of 0.05 resulted from the optimisation procedure. However, it is important to underline that even if these simulations give the maximum attainable plant efficiencies (in terms of equilibrium calculations), in real plants satisfactory steam gasification performance is only reached using higher SC ratio values (1-3). In fact, from a practical point of view, it is more important to produce a low tar - and high heating value - syngas, in order to assure greater process reliability and longer plant life.

For all the plant layouts and feedstocks considered the syngas molar composition was quite similar (average dry gas composition 51.3% H₂, 42.7% CO, 1.5% CH₄, 0.2% N₂ in the gasification temperature range 750 - 830°C) due to the similarity of the biomass compositions. Since all the compositions presented refer to the syngas after the clean-up stage, the gas water content is negligible for the first and second layouts (wet clean-up system).

Finally, Figures 6 and 7 show all the calculated flows using the mass balance of the simulation of the whole plant process for the reference case of pine sawdust conversion.

8. Energy analysis

The heat and mass fluxes have been characterised for each feedstock (always considering the reference basis of 1kg/h of inlet biomass) in order to assess the global efficiency. Since the plant layout permits both heat and electric power generation, the thermal and electrical efficiencies have been evaluated separately.

The energy balance has been optimised for the whole process in order to assess the global efficiency. The used and the recovered energy have been calculated in terms of electricity, heat and mechanical energy for the thermal-conversion and power-generation sections.

The evaluation of the electrical energy produced has been carried out:

- computing the net electrical energy produced by the gas engine for the assumed efficiency (35%) (layout 1);
- computing the net electrical energy produced by the gas and the steam turbines and subtracting the energy needed by the compressors and the pump from the turbine expansion work (layout 2).

A 99% efficiency has been assumed for the alternators in the second layout. Although the compression and expansion isentropic efficiencies have been assumed to be equal to 80% (for the steam turbine) and 90% (for the gas turbine).

In the simulation the clean-up system energy consumption has not been considered: however this can be estimated to be less than 3×10^{-3} kWh Nm⁻³ (specific value relevant to the gas subjected to the purification treatment).

The thermal energy consists of the fraction recovered from the syngas and flue gas streams. On the syngas stream:

- where no steam is piped to the gasifier (layout 2), the entire contribution before the syngas clean-up is recovered for heat generation at a temperature of approximately 800°C;
- in layout 1, there is a heat recovery stage after the steam generator as in the above- mentioned configuration.

Similarly, it is possible to consider an equivalent recovery process at the flue gas outlet in the IC gas engine plant, where the fraction of recovered thermal energy is simply computed by means of the assumed thermal efficiency (40%) considering a discharge flue gas temperature of 150°C.

Heat exchanger efficiency has been assumed to be 75% for the processes involving only the gas phases, and 85% in the case of a liquid-gas heat exchange process.

The plant efficiency has been calculated for electric power generation in the case of CHP production. The latent heat has not been taken into account in the recovery of the available thermal energy from the exhaust gases since the efficiency calculations were based on the lower heating value of the feedstock.

Table 7 shows the global efficiencies obtained from the sum of the electric and thermal power versus the inlet thermal power based on the lower heating value and a reference feedstock mass flow of 1 kg/h.

Figure 8 shows the electrical and global efficiency computed for the two layouts with reference to the lower heating *value* (average value of the feedstocks considered).

The results obtained show that the average value of the electrical efficiency in layout 2 is significantly greater (40.7%) than in layout 1 (31.1%). However, the global efficiency of IC engine based layout (73%) is higher than that of the gas turbine based layout (47.5%). The lower global performance of the second layout is mainly due to the configuration adopted that maximises the electrical production to the detriment of thermal energy recovery.

It is also important to underline that the major part of the energy loss is due to the difficulty of recovering the thermal energy wasted by the scrubber (inlet and outlet temperatures of about 150 and 30°C respectively). A minor energy loss arises from the

enthalpy of the ash exiting the thermal conversion section and from the unrecovered heat from the exhausts in the temperature range 20-30°C.

9. Environmental analysis

The plant exhaust emission composition and mass flow have been computed for each feedstock considered. The final results are presented by comparing the main chemical species average concentrations (Figure 9) and the CO₂ specific emission (Figure 10) for the plant configurations adopted.

The flue gas composition is proportional to the amount of comburent air used for the burning stages, thus, the IC gas-engine plant presents the lowest CO₂ concentration as it works in almost stoichiometric conditions.

Nevertheless, it is more useful to compare the CO₂ mass flow exiting the plant and, especially, the specific emissions. These results show that 1kWh of electrical energy generated using an IC gas engine coupled with a CFB gasifier plant has an environmental cost (in terms of greenhouse emissions) that is 41% higher than that using an equivalent gas turbine.

Moreover, the carbon dioxide evaluated at the plant outlet is generated by means of renewable energy sources and then the emission balance should be correctly assessed with a life cycle analysis taking into account all the steps from the source production to its exploitation.

10. Comparison with a fuel cell system

This paragraph provides a brief comparison of the present analysis and a previous work carried out by the authors on an MCFC (Molten Carbonate Fuel Cell) system [1], pointing out differences - or similarities - in both the configuration and balance of the plant.

The fuel cell system was based on the same concept of biomass energy upgrading, but the syngas obtained by means of pyrolysis or gasification was directly fed to an MCFC generator.

The main advantage was the high electrical efficiency of the MCFC device, but some difficulties arose, for example the higher fuel cell sensitivity to syngas contaminants.

In particular, as MCFCs operate at high temperatures (about 650°C), a dry gas cleaning system was foreseen for the syngas stream in order to minimise thermal energy losses.

The chosen gas purification system consisted of a first heat exchanger, a first cyclone, a zinc oxide reactor, a sodium carbonate reactor, a second heat exchanger, and a second cyclone followed by an electrostatic precipitator and a ceramic filter [34].

Another difference was that sintered dolomite was assumed to be mixed with the sand in the reactor bed to promote cracking in the gasifier, making it possible to eliminate a separate cracking unit [35].

The system simulation was performed with the same approach and tools described in

the present paper. The energy balance assessment was carried out computing the electrical energy produced by the MCFC and the exhaust gas expansion turbine (as the stack operates at 3.5 bar) minus the auxiliary consumptions. The thermal energy consisted of the fraction recovered from the syngas and flue-gas streams. The calculated average values of the plant efficiencies were greater than those estimated in the present work, specifically about 45% for the electrical efficiency and 75% for the global value.

The MCFC plant layout was also characterised by the best environmental performance in terms of greenhouse gas emissions - comparable with the estimated value of the CCGT plant - with a specific CO₂ production of 0.9 kg kWh_{el}⁻¹ relevant to an average mass flow = 1.9 kgCO₂ h⁻¹ kg_{biomass}⁻¹.

11. Conclusions

In this paper different plant solutions have been analysed to determine the advantages of the use of biomass-derived syngas in terms of energy and environmental balances. Bagasse, pine sawdust, poplar sawdust and almond shells have been considered as potential renewable sources and similar results have been obtained for all.

The application of IC engines and CCGT plants has been discussed and it has been demonstrated that the CCGT plant has the better electrical efficiency (about 40%) and the minimum thermal energy production.

On the other hand, the IC engine configuration is characterized by a significant thermal energy fraction, which, if exploited, makes it possible to reach global energy efficiencies higher than 70%. This energy fraction is released at high temperatures on the syngas line and at the burner exhaust outlet: as most of the heat is recovered from exhausts (at lower temperatures), it would be particularly beneficial to exploit it for feeding a district-heating plant network.

The IC engine and CCGT based plants have been also compared with a system where the syngas is fed to fuel cell devices. The syngas-fuel cell solution gives better performances (electrical efficiency of about 45%). However, the use of biomass syngas in traditional traditional power generators such as IC engine and CCGT is a valid way to reduce environmental impact and so could promote a greater diffusion of biomass use for energy production being a more “ready to market” technology.

So, the IC engine plant layout seem to be suitable for small size CHP plants (100 - 1000 kW_{el}), since the thermal power produced can be exploited at the local scale, avoiding the installation of an extended and expensive district heating network.

The CCGT plant could be reasonably scaled up to medium sizes (10 - 20 MW_{el}), as it mainly generates electrical energy. Greater plant sizes are rarely used because of problems related to biomass procurement and storage.

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Figure captions

Figure 1. Schematic diagram of the reference plant, layout 1 (data referring to pine sawdust case).

Figure 2. Schematic diagram of the reference plant, layout 2 (data referring to pine sawdust case).

Figure 3. Simulink environment: syngas production section in layout 2.

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Figure 6. System mass balance referring to 1 kg/h biomass basis, layout 1 (pine sawdust case, $T_{\text{gasification}} = 760^{\circ}\text{C}$, $\text{SC}=0.05$).

Figure 7. System mass balance referring to 1 kg/h biomass basis, layout 2 (pine sawdust case, $T_{\text{gasification}} = 771^{\circ}\text{C}$, $\text{SC}=0$).

Figure 8. Electrical and global efficiency with respect to lower biomass heating value (average value of the feedstocks considered).

Figure 9. Plant-exhaust emission characterisation: average molar percent composition.

Figure 10. Plant exhaust emission characterisation: CO_2 average specific emission (mass flow = 1.5 [layout 1] and 1.6 [layout 2] $\text{kg}_{\text{CO}_2} \text{h}^{-1} \text{kg}_{\text{biomass}}^{-1}$).

Table 1. Process parameters for the wet gas-cleanup (d = particle diameter) [22].

Plant unit	Process parameters	Value
Cyclone	Temperature	120-150°C
	Pressure loss	0.5-1 kPa
	Removal efficiency	50-80% (d<5μm)
		80-95% (5<d<20μm)
		80-95% (5<d<20μm)
		95-99% (20<d<50μm)
95-99% (d>50μm)		
Energy demand	0.15-0.3 ×10 ⁻³ kWh Nm ⁻³	
Bag filter	Temperature	120-130°C
	Pressure loss	1.5-2.5 kPa
	Removal efficiency	> 99%
	Energy demand	0.3-1.2 ×10 ⁻³ kWh Nm ⁻³
Scrubber	Temperature (in)	120°C
	Temperature (out)	30°C
	Pressure loss	0.6-2.5 kPa
	Removed diameter (50% eff.)	0.7–1.5μm
	Energy demand	0.2-1.5 ×10 ⁻³ kWh Nm ⁻³

Table 2. Parameters adopted for the 1st plant layout.

Plant unit	Process parameters	Value
IC gas engine	Temperature syngas (in)	30°C
	Temperature exhausts (out)	150°C
	Thermal efficiency	40%
	Electrical efficiency	35%

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Table 3. Parameters adopted for the 2nd plant layout (pine sawdust case values).

Plant unit	Process parameters	Value
Gas turbine engine	Temperature, syngas (in, compressor)	30°C
	Temperature, air (in, compressor)	20°C
	Temperature, fuel (in, turbine)	1187°C
	Temperature, exhausts (out, turbine)	643°C
	Equivalence ratio	3.35
	Pressure ratio	10
	Isentropic expansion coefficient	90%
	Isentropic compression coefficient	90%
HRSG	Temperature, flue gas (in)	704°C
	Temperature, flue gas (out)	220°C
	Temperature, water (in, economiser)	20°C
	Temperature (evaporator)	250°C
	Temperature, steam (out, super-heater)	487°C
	Economiser efficiency	65%
	Evaporator efficiency	65%
	Super-heater efficiency	50%
	Pressure	40bar
Steam turbine	Isentropic expansion coefficient	80%
	Isentropic compression coefficient	80%

Table 4: Characteristics of biomasses considered

	Bagasse [29]	Pine sawdust [30]	Poplar sawdust [30]	Almond shells [30]
Moisture [%w]	7.1	9.4	10.0	11.50
Ash [%w]	0.9	0.9	3.9	2.9
C [%w]	46.0	45.2	43.1	40.9
H [%w]	5.4	5.4	5.1	5.2
O [%w]	40.4	39.0	37.7	38.60
N [%w]	0.2	0.1	0.2	0.9
LHV [MJ/kg]	16.2	16.4	15.5	16.0

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Table 5. Calculated conversion temperatures of the considered feedstocks.

		Bagasse	Pine sawdust	Poplar sawdust	Almond shells
Conversion temperature [°C]	Layout 1	750	760	750	750
	Layout 2	777	771	757	765
SC	Layout 1	0.10	0.05	0.05	0.05
	Layout 2	0.00	0.00	0.00	0.00

Table 6. Syngas characterisation: molar percent composition (dry basis).

		Bagasse	Pine sawdust	Poplar sawdust	Almond shells
Layout 1	H₂	51.2	51.9	51.5	50.8
	CO	43.4	42.4	41.5	42.4
	CO₂	3.9	4.0	5.1	4.6
	CH₄	1.4	1.6	1.8	1.6
	N₂	0.1	0.1	0.1	0.6
Layout 2	H₂	51.3	51.9	51.5	51.0
	CO	41.0	41.5	40.8	40.9
	CO₂	5.7	4.8	5.7	5.7
	CH₄	1.9	1.7	1.9	1.8
	N₂	0.1	0.1	0.1	0.6

Table 7. Plant efficiency.

	Biomass	Thermal power input (kW)	Electric power output (kW)	Thermal power output (kW)	Electrical efficiency [%]	Global efficiency [%]
Layout 1	Bagasse	4.50	1.42	1.89	31.6	73.5
	Pine sawdust	4.56	1.40	1.90	30.7	72.4
	Poplar sawdust	4.31	1.33	1.80	30.9	72.6
	Almond shells	4.44	1.39	1.87	31.3	73.4
Layout 2	Bagasse	4.50	1.84	0.31	40.8	47.6
	Pine sawdust	4.56	1.87	0.31	40.9	47.8
	Poplar sawdust	4.31	1.74	0.29	40.3	47.1
	Almond shells	4.44	1.81	0.31	40.6	47.6

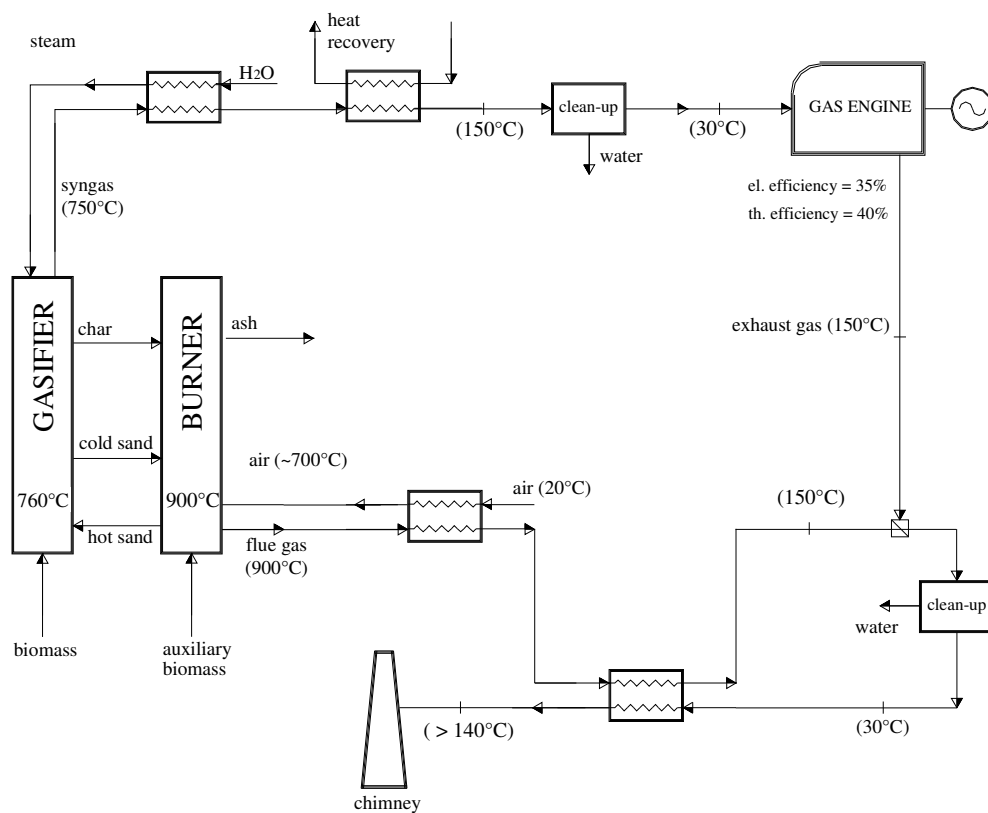


Figure 1. Schematic diagram of the reference plant, layout 1 (data referring to pine sawdust case).

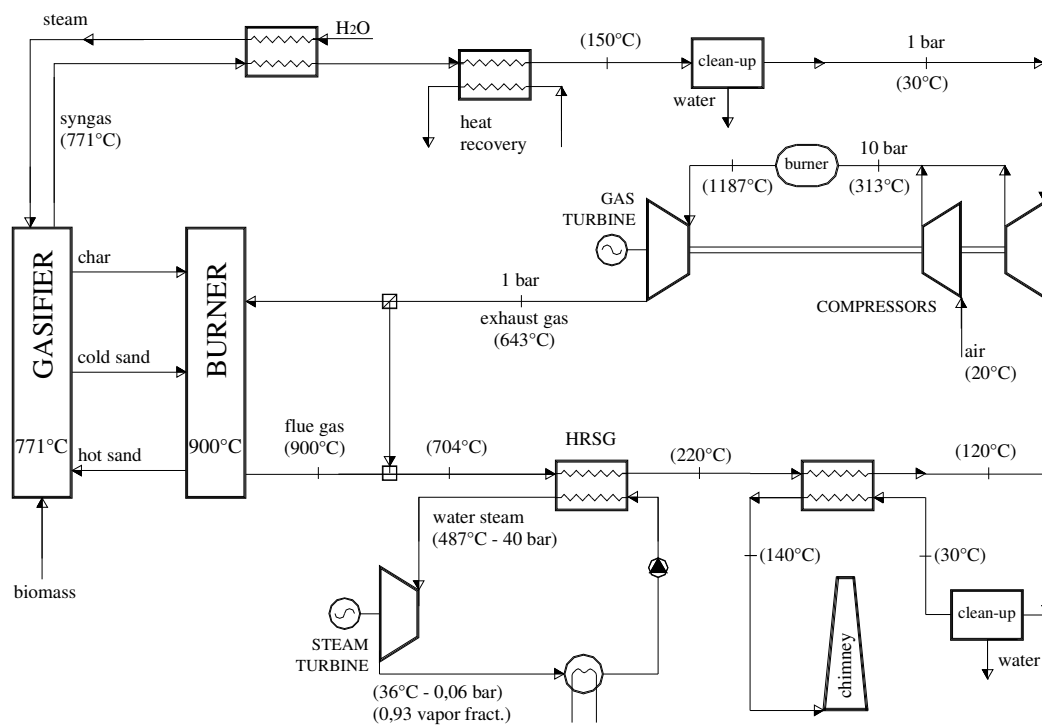


Figure 2. Schematic diagram of the reference plant, layout 2 (data referring to pine sawdust case).

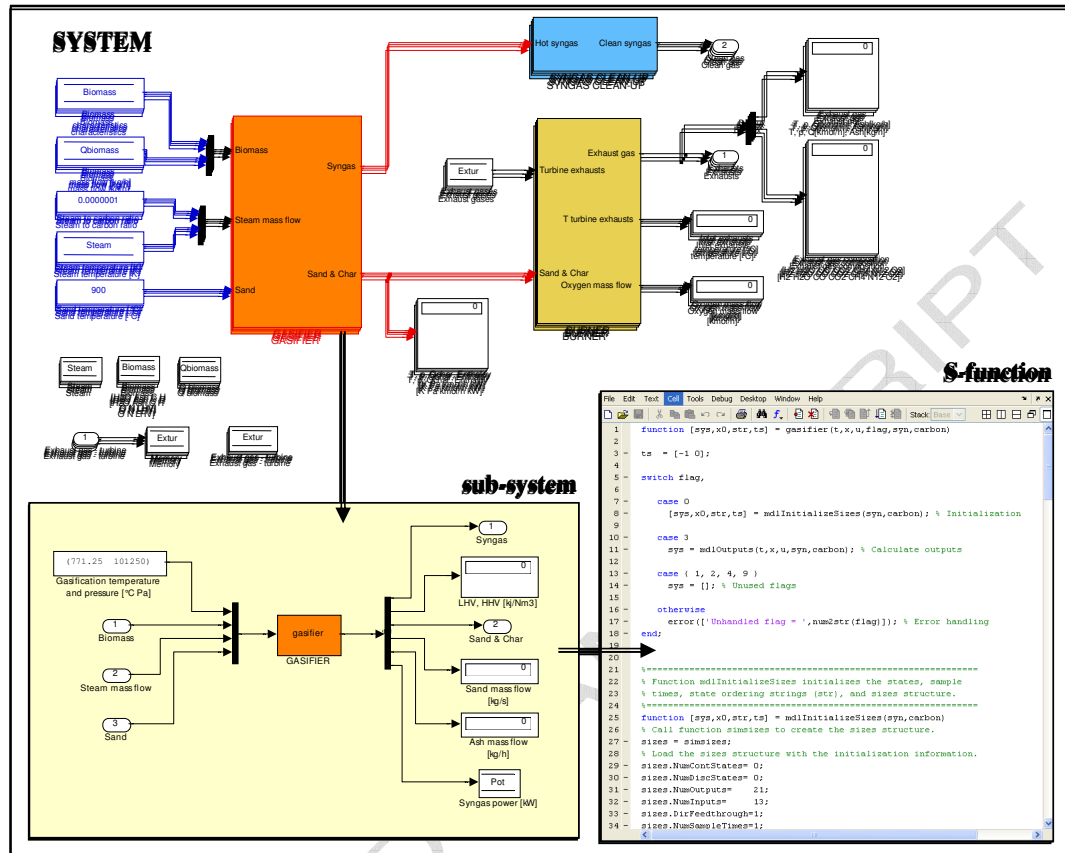


Figure 3. Simulink environment: syngas production section in layout 2.

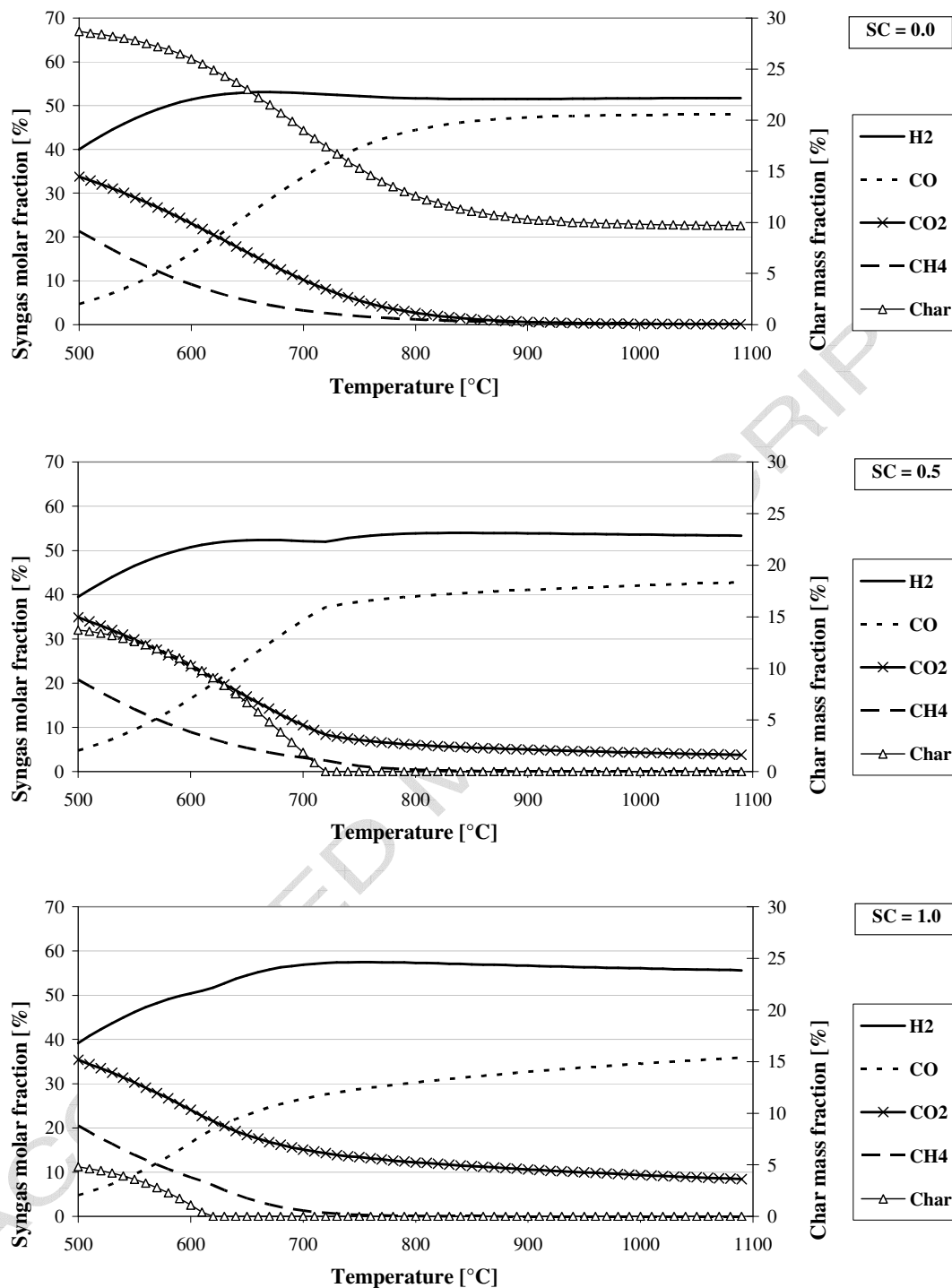


Figure 4. Gaseous and solid products from the thermal conversion of pine sawdust as a function of the temperature for different SC values.

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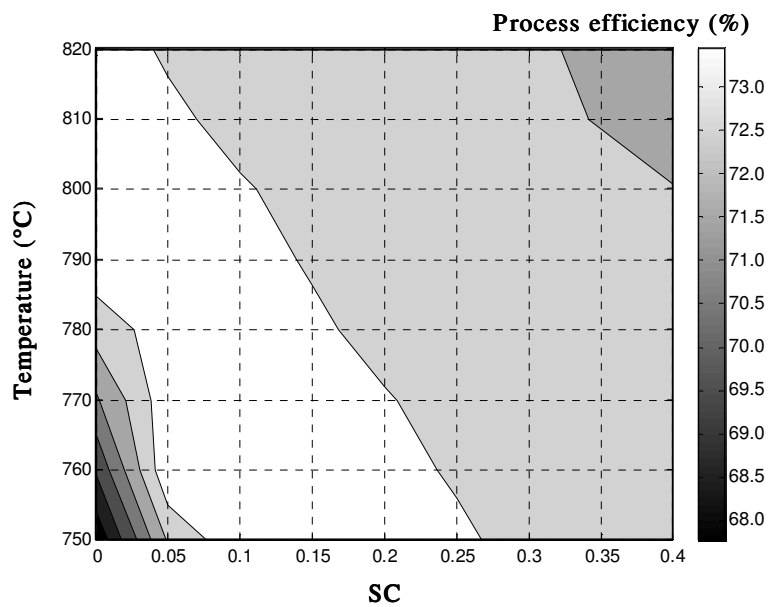


Figure 5. Optimisation of the conversion process (layout 1 – pine sawdust case).

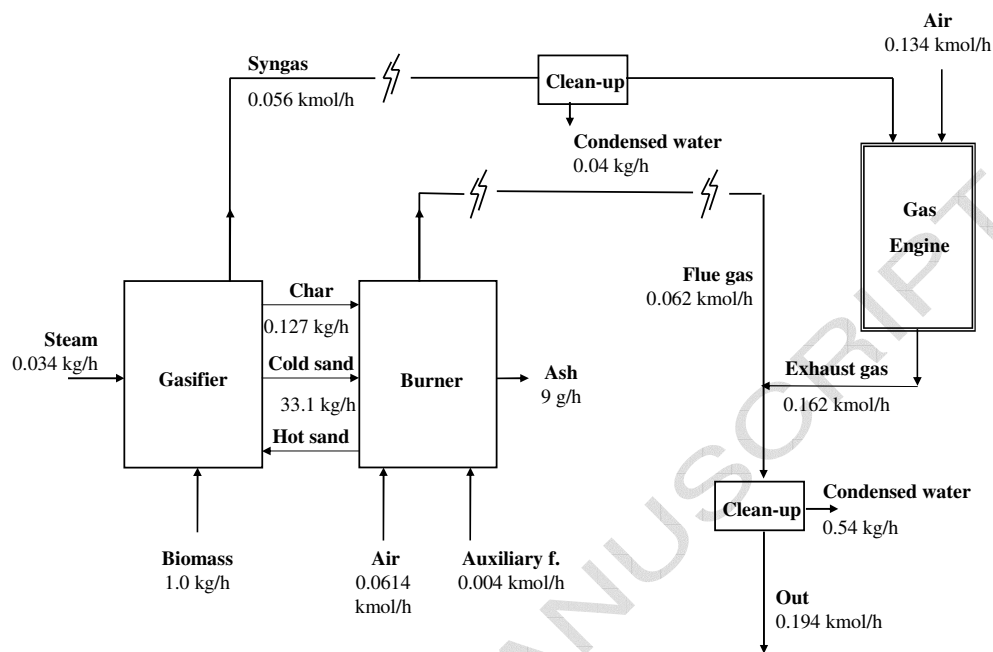


Figure 6. System mass balance referring to 1 kg/h biomass basis, layout 1

(pine sawdust case, $T_{\text{gasification}} = 760^{\circ}\text{C}$, $\text{SC}=0.05$).

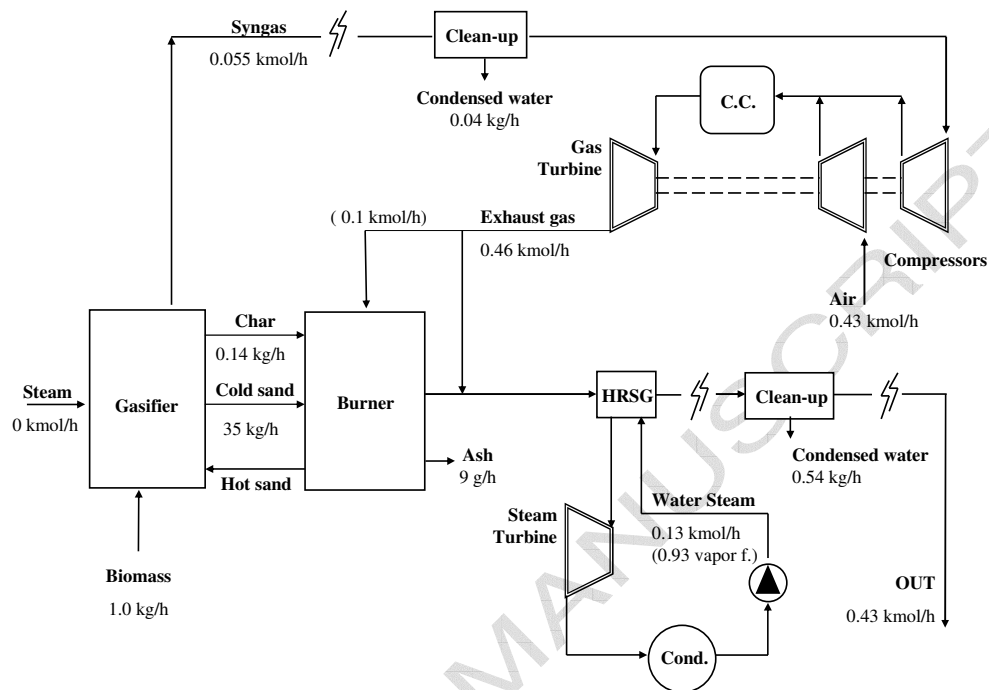


Figure 7. System mass balance referring to 1 kg/h biomass basis, layout 2

(pine sawdust case, $T_{\text{gasification}} = 771^{\circ}\text{C}$, $\text{SC}=0$).

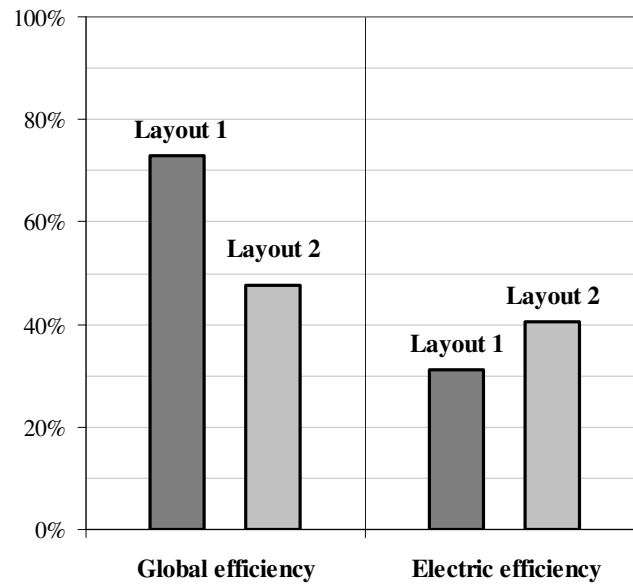


Figure 8. Electrical and thermal energy production efficiency with respect to lower biomass

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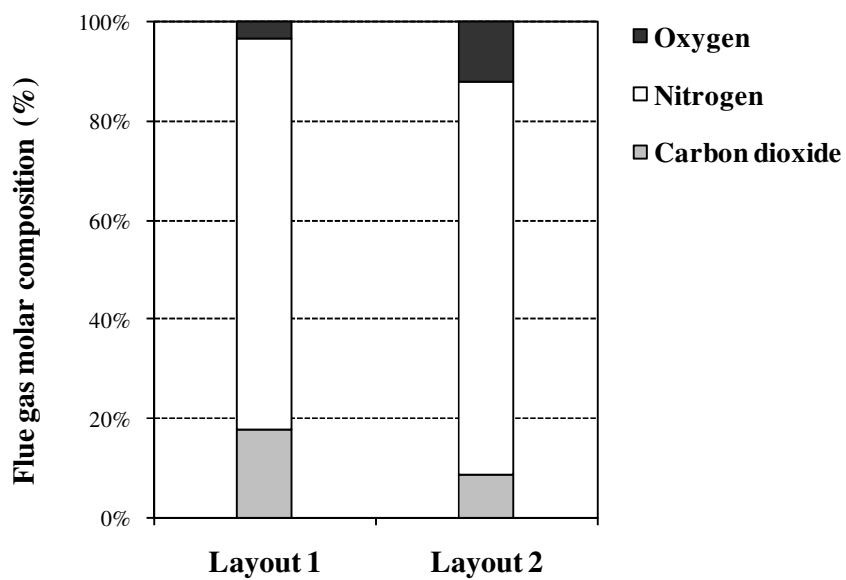


Figure 9. Plant-exhaust emission characterisation: average molar percent composition.

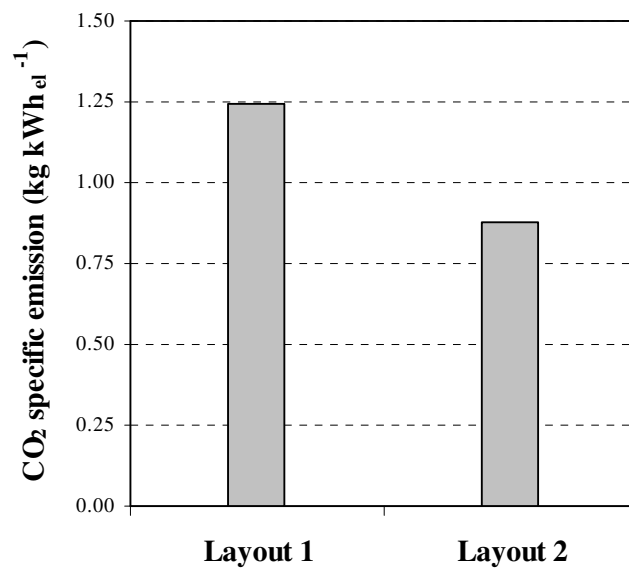


Figure 10. Plant exhaust emission characterisation: CO₂ average specific emission

(mass flow = 1.5 [layout 1] and 1.6 [layout 2] kg_{CO₂} h⁻¹ kg_{biomass}⁻¹).