68th Conference of the Italian Thermal Machines Engineering Association, ATI2013

State of art of small scale biomass gasification power systems: a review of the different typologies

Bocci E.[a,*], Sisinni M.[b], Moneti M.[c], Vecchione L.[c], Di Carlo A.[b], Villarini M.[c]

[a]Engineering Faculty, Energy Department, Marconi University, Rome 00143, Italy
[b]Engineering Faculty, Mechanic Department, Sapienza University, Rome 00184, Italy,
[c]Interdepartmental Centre for Research and Dissemination of Renewable Energy, Tuscia University, Orte (VT) 10160, Italy

Abstract

The security of supply and climate change issues and the linked recent growth of the local power generation by means of renewable energies technologies are providing real opportunities for the development of small scale biomass gasification systems. The present paper reports the state of art of the small scale gasification power plants. Initial attention has been given to the different biomass feedstock suitable for gasification, focusing on residues with low cost and low environmental impact. Then the two major typologies of gasifiers (fixed and fluidized bed) have been analyzed in terms of raw gas yield, composition and tar and particulate content. The different cold and hot raw gas conditioning systems, highlighting their compatibility with the different gasification system, are described. High efficiency examples of power production by means of internal combustion engine, micro gas turbine, Solid Oxide Fuel Cell or a mix of them, both as realized plants and process simulated ones, have been then reported. The paper provides an overview of the different power plants in terms of efficiency, reliability and cost.

1. Introduction

World's energy system needs to be adapted into a more sustainable one, based on a diverse mix of energy sources, addressing the pressing challenges of security of supply and climate change. Medium-large (1-50 MW$_{th}$) coal and biomass gasification power plants are developed and planned. These power plants can effort, owing to the size,

---

advanced pre-processing, gasification and gas conditioning technologies. Regarding the small power plants, the technology development issues still remain. Nevertheless, to really exploit the biomass energy potential, reliable, high efficiency and low environmental impacts small scale power plants have to be developed, to follow the low energy density and perishability of this fuel [1], [2]. Indeed, one of the major limitations associated with the use of the large bioenergy potential (e.g. the Italian territory amounted to about 30 million metric tons/year [3]–[5]) is the biomass dispersion. Actually, a small biomass power plant can have annual operating hours lower than 7000, efficiency lower than 25%, high local and environmental impacts and a capital cost greater than 10.000 €/kWhe [6]. Analysing the small scale power plants, initial attention has been given, to the different biomass feedstock suitable for gasification, focusing particularly on residues with low cost and low environmental impact.

Nomenclature			
t	ton (1000 kg)	LHV/HV	Low Heating Value / Heating Value
MSW	Municipal Solid Waste	TAR	Topping Atmosphere Residues
VM	Volatile Matter	FX	Fixed Carbon
%vol/wt	% in volume/weight	UD	Updraft gasifier
DD	Downdraft gasifier	CFB/FB	Circulating / Fluidised Bed gasifier
ER-S/B	Equivalent - Steam to Biomass ratio	ICE	Internal Combustion Engine
mGT	micro Gas Turbine	FC/SOFC	Fuel Cell / Solid Oxide Fuel Cell
m,P	mass flow, Power	Uf	fuel utilization factor
J	current density	TIT	Turbine Inlet Temperature

2. Biomass

Biomass is the fourth world-wide energy resource (following oil, coal and natural gas) but the energy use of the organic substances is limited by their low energy density, complexity of the supply chain (often in competition with the main uses of organic matter, as food and materials) and high local emissions of pollutants [7]. Using organic wastes as feedstock in high efficient micro-cogeneration plants would solve all the old-actual drawbacks associated to biomass utilization as energy source. For the selection of the feedstock to be used in gasification processes, the first criterion to be considered is the biomass availability on a significant scale (t/year). In every energy conversion process, because of energy needs in terms of efficiency and power density, fuels with a high LHV are favorites. This meaning that biomass with lower humidity is preferable. Seasoning can reduce the moisture content or the excess of heat produced by the power plant could be exploited to dry biomass in order to use also biomass with 50% of moisture. The density affects significantly any freight and storage. Furthermore, in fluidized bed gasifier to have a good mixing between fuel and bed material, the biomass density should be comparable with that of the bed. Another important feature that must be considered is the size and shape of the biomass feeding the gasifier. Biomass must be processed to a uniform size or shape to feed into the gasifier at a consistent rate and to ensure homogeneous and efficient gasification. This can lead to significant costs for the shredding: chip size (1-2 cm) is at the moment the right compromise. The chemical composition (C, H, O, N, S, Cl) is another important aspect that must be considered [8], [9]. For lignocellulosic biomass the chemical composition (expressed on a dry and ash free basis) is generally more constant than that of other solid fuels (MSW, coal). Furthermore, more than 80% of the biomass is volatile the remaining 20% is charcoal. Coal is typically only 20% volatile, while the remaining 80% is unreactive coke, which is more difficult to gasify than charcoal. Generally biomass has very low Sulphur and Chlorine content compared to coal and MSW. Only in some cases, e.g. Fuel Cells, severe cleaning procedures are required to meet the specifications of these systems, see power technologies chapter. Finally, Ash and TAR contents are one of the main obstacles to economical and viable applications of biomass gasification technologies, see gas conditioning chapter. Fuel with a high ash content require greater attention because ash brings sintering, agglomeration, deposition, erosion and corrosion problems Furthermore they are elutriated by the producer gas, thus more is the ash content and much more problematic will be the gas cleaning procedures. TAR condenses at high temperature, causing clogging and damage to the downstream equipment. To sum up, the most suitable biomass for gasification must have availability on significant scale (t/year) and a good physical (low water content and high bulk density) and chemical

characteristics (high Caloric Value, high volatile substances, low ash, high Carbon to Nitrogen ratio, low Chlorine and Sulphur content). The focus, as mentioned earlier, is on biomass waste like "shells" (of pine, hazel, walnuts and almonds); "pruning" (of beech, oak, spruce, poplar, willow, eucalyptus, grape, olives); "straws" (of wheat, corn, rye, barley, rice); an example of agro-industrial residue (dry exhausted olive), an example of energy cultivation (Miscanthus). Table 1 shows the chemicals and physics properties of these different kind of biomass. The table shows that the shells have the more suitable characteristics (low humidity content not great variable, high density, low ash content, high calorific value). Prunings have a greater variation of the characteristic. Straws not only have a larger characteristic variation, but also a higher ash content that in many case have a melting temperature lower than the gasification temperature and thus clog the reactor. Regarding the CHO the lignocellulosic biomass has almost the same wt percentage (respectively 41-51, 5-6, 36-44). N, Cl, S accounts for very low percentages that vary depending on the biomass typologies and cultivation characteristics (soil, fertilizers, etc.).

Table 1 Chemicals and physics biomass properties [10]

Biomass typologies	Humidity (%wt)	Bulk Density (kg/m^3)	Ash (%wt)	VM (%wt)	FX (%wt)	C (%)	H (%)	N (%)	O (%)	Cl (%)	S (%)	LHV (MJ/kg dry)
Shells	11-14	300-500	1-2	74-78	20-25	48-51	6	0.2-0.5	41-44	0.02-0.03	0.01-0.03	18-20
Pruning	7-25	200-300	0.5-4	70-85	12-20	45-49	5-6	0.1-0.8	36-44	0.01-0.08	0.01-0.08	16-18
Straw	7-12	20-140	5-15	67-76	16-18	41-47	5-6	0.3-6	36-44	0.03-0.4	0.04-0.2	15-18
Exhausted olive	9	350	4	77	19	51	6	0.3	38	0.02	0.02	20
Miscanthus	4	240	5	71	19	45	5	0.5	40	0.2	0.08	18

3. Gasification technologies

Gasification is a thermo-chemical process that converts biomass through partial oxidation into a gaseous mixture of syngas consisting of hydrogen (H_2), carbon monoxide (CO), methane (CH_4) and carbon dioxide (CO_2) [11]. The oxidant can be air, pure O_2, steam, CO_2 or their mixtures, and it is the main parameter affecting the syngas composition, as shown in Table 2. Air is the most used gasifying agent, due to the great availability and zero cost, but the large amount of nitrogen not only requires higher power on blowers and bigger equipment but especially lowers the heating value of the syngas produced. Pure O_2, avoiding the nitrogen content, increases the syngas heating value but also the operating costs due to the O_2 production. Steam, due to the great availability and about zero cost of water, increases the heating value and H_2 content of syngas, and can be produced using the excess of heat of the power plant [12]. Herguido et al. [13] showed an increase in H_2 (as high as 60%) and CO_2 (from 10 to 30%) contents, a decrease in CO (from 35 to 10%) content, and a slight decrease in CH_4 content when the S/B ratio was increased from 0.5 to 2.5. CO_2 increases the heating value and H_2 and CO content of syngas, but it must be available. Steam or CO_2 requires heat supply for the endothermic gasification reactions. This can be done indirectly, circulating a hot material or using heat exchangers, or directly, feeding the gasifier via also air [14] or O_2 [15] to partially burn the biomass. The hot material in fixed bed has to go mechanically from the combustion to the gasification reactor; meanwhile in fluidized bed, the material can circulate via the different pressure /bed high. In any case, the exhaust fumes don't come into contact with the product gases, which so have high HV.

Table 2 Syngas composition with different oxidant [16], [17]

Oxidant	Composition (vol%)					
	H$_2$	CO	CO$_2$	CH$_4$	N$_2$	LHV(MJ/Nm^3)
Air	9÷10	12÷15	14÷17	2÷4	56÷59	3÷6
Oxygen	30÷34	30÷37	25÷29	4÷6	-	10÷15
Steam/CO$_2$	24÷50	30÷45	10÷19	5÷12	-	12÷20

Gasifiers can be divided into two main families [18], fixed bed (from which are derived the moving bed) and fluidized bed. Within the fixed bed gasifiers it is possible to distinguish updraft (UD) configuration (countercurrent) when biomass move from the top and the gasifying agent from the bottom; downdraft (DD) configuration (concurrent), when the biomass and the gasifying agent move together from the top to the bottom of the reactor; crosscurrent when the biomass moves down and the agent is fed at right angles. In the UD the downward-moving biomass is dried and pyrolysed, giving char which continues to move down to be gasified, and pyrolysis vapors

which are carried upward by the upflowing hot product gas. The tars in the vapor either condense on the cool descending fuel or are carried out of the reactor with the product gas, contributing to its low ash but high tar content (up to 100 g/Nm³). Because the extremely high tar content in the gas this configuration is more suitable for direct firing, like the small cooking stoves. In the DD the biomass together with the oxidant is forced to pass through a constriction (throat) where most of the gasification reactions occur. The reaction products are intimately mixed in the turbulent high-temperature region around the throat (1100-1200 °C), which aids tar cracking. This configuration results in a relatively clean gas from tar (< 10 g/Nm³) even if particulates in gas can be high. The high residence time of biomass leads to a high char conversion (≈95 %). Because the gases leave the gasifier unit at temperatures about 900–1000 °C, the overall energy efficiency of a downdraft gasifier is low, due to the high heat content carried over by the hot gas. Downdraft is generally utilized for small-scale electricity generation with an internal combustion engine. Downdraft gasifiers are not suitable for scale-up to larger sizes (> 1 MW) because they do not allow for uniform distribution of flow and temperature in the constricted area (throat). A crossdraft gasifier is a co-current moving-bed reactor, in which the fuel is fed from the top and air is injected through a nozzle from the side. One of its important features is a relatively small reaction zone with low thermal capacity, which gives a faster response time than that of any other fixed-moving-bed type. Because its tar production is low (0.01–0.1 g/Nm³), a crossdraft gasifier requires a relatively simple gas-cleaning system.

In the fluidized bed gasifiers (FB) the solid fuel, mixed with hot bed material (inert sand, catalyst), are kept in a semi-suspended condition (fluidized state) by means of the gasifying medium through them at the appropriate velocities. called minimum fluidization velocity [19]. Unlike the fixed bed gasifier, because the intense gas-solid mixing, the different zone of drying, pyrolysis, oxidation and reduction, cannot be distinguished. Thanks to the excellent gas-solid mixing and to the large thermal inertia of the bed, the temperature and the solid/gas concentration are uniform in the entire bed. For these reasons the biomass conversion in the FB is close to 100% and the throughputs (biomass flow rate per installed reactor area) are double to ten times higher than in the fixed beds (500-1000 $kg_{biomass}$/h m²). For the same reasons, differently to fixed bed gasifiers, which need a fairly specific feedstock, FB are in general more tolerant and suitable for large installations. E.g. FB operate with uniform and relatively low temperatures (700-900 °C): most high-ash content fuels, depending on ash chemistry, can be gasified without problems of ash sintering and agglomeration. Finally FB don't require high temperature moving mechanical components (e.g. moving grids like in the moving bed) because the mixing effect is guaranteed in excellent way by the fluidization state. Because of these advantages, most of the current development activities are focused on large-scale FB. However FB still have the following disadvantages. The operation, even if more flexible than fixed bed, is more complicated. The concentration of particulates in the gas is generally higher (from 10 to 100 g/Nm³). The fast movement of the bed material generates high abrasive action. Finally tar production for fluidized bed gasifier lies between that for updraft (~50 g/Nm³) and downdraft gasifiers (~1 g/Nm³), with an average value of around 10 g/Nm³. The concentration can be reduced to few g/Nm³ adding natural catalyst like olivine as gasifier bed [16].

4. Process parameters

As mentioned earlier the main parameters are the fuel and oxidant quantity and physical and chemical composition; the process temperature; the residence time. The *biomass composition* influences the syngas composition and therefore LHV and chemical efficiency, defined by the following formula:

$$\eta_{chem} = \frac{m_c * LHV_c}{m_b * LHV_b} \qquad (1)$$

Where m_c is the product fuel, LHV_c is the fuel LHV, m_b is the input biomass and LHV_b is the biomass LHV. The second important parameter is the *oxidant/biomass ratio*, defined by the following formula:

$$\frac{O}{B} = \frac{kg/h \; of \; oxidant \; and \; water \; in \; biomass}{kg/h \; of \; dry \; biomass} \qquad (2)$$

The equivalent ratio (ER) is the ratio between the amount of oxidizing agent used and the stoichiometric amount (the theoretical amount of any oxidizing agent required to burn the fuel completely). Thus generally it is used the ER (always less than 1 in a gasification process) instead of the oxidant/biomass ratio but, using steam as oxidant, is common used the steam to biomass ratio. The gas product LHV depends on the presence of H_2, CH_4 and CO. The

concentrations of these species in the output gas varies, varying temperature and ER, e.g. increasing temperature and S/B (in case the oxidant is steam) CH_4 decrease, instead H_2 and CO increase. In a thermochemical process a low *temperature* induces slow conversion processes, low conversions, and a greater production of CH_4 and CO_2 to the detriment of H_2 and CO. To achieve a high carbon conversion of the biomass and low tar content, a high operating temperature (above 800°C) in the gasifier is preferred. Yu et al. [20] demonstrated that an increasing temperature promotes the formation of gaseous products at the expense of total tar. More than 40% reduction in tar yield was reported when the temperature was raised from 700°C to 900°C. Narvaez et al. [21] demonstrated that changing the bed temperature of the bubbling fluidized bed from 700°C to 850°C there was a drastic decrease(about 74% less) in TAR content. According to Kinoshita et al. [22] TAR yield and TAR concentration decreases as the ER increases because of more availability of oxygen to react in the pyrolysis zone. This effect of ER is more significant at higher temperature. If the ER value is high, low concentrations of H_2, CO and higher CO_2 content in the product gas are obtained. The residence time, given by the length of the reactor and the gas velocity ratio, influences gas composition and carbon conversion. In general increasing the residence time (less than 20 s), carbon conversion, gas yield, and H_2 and CO concentrations increase, while CH_4 and CO_2 content decrease. The residence time has little influence on the TAR yield, but it significantly influences the TAR composition [22].

5. Gas conditioning technologies

A clean-up – gas conditioning system is always necessary before to exploit the producer gas into a power system. These systems normally have encumbrance and cost even greater the gasifier unit, thus they can be regarded as the unavoidable secondary unit in a gasification power plant. The gas conditioning technologies can be primarily divided following the physical apparatus where they are applied: downstream (secondary methods) or inside (primary methods) the gasifier. The *secondary methods* can be subdivided into two main categories based on the working temperature: Cold and Hot methods. The *cold methods* are mainly divided in "dry" methods (*bag and sand filter*) and "wet" methods (*scrubber*). The first one works at a temperature about 150-250°C. They have an efficiency of about 99% to separate the particulate, and about 20-80% (depends of temperature, active filter surface) to TAR separation. In the scrubber the gas cools down to 25-55°C, encountering cold water jet. In this way the scrubber removes particulate, TAR and nitrogen compounds. The disadvantage of this technology is the gas cooling and a water treatment downstream system. The water treatment can be avoided using vegetable oil or biodiesel or other TAR solvents instead of water, in order to not only increase the TAR removal but especially feed the gasifier with these fuels avoiding the treatment and guarantee the heat supply for the gasification reactions. The first stage of the *hot methods* consists of a cyclone, which removes all the char and part of the particulate, using centrifugal and gravity force, then there are systems to remove TAR and the remaining particulate. The *cyclone* is present in all the fluidized bed reactors, and it works in a wide temperature spectrum. In general the cyclone can removes over the 90% of particles with diameter upper than 5 μm, it is partially efficient with the particle size between 1 and 5 μm, and it is ineffective for particles with diameter lower than 1 μm. The *TAR cracking* is used to remove TARs and to break down the alkali. The system consists in the introduction of a catalytic material into a secondary reactor. TARs and alkali condense on the catalyst surface which recirculating in the combustion zone burn the TARs. The *high temperature filters* separates, through adsorption, Sulphur and Chlorine compounds and filter fine particles, and they can be ceramic or metallic. The *primary methods* include gasifier modifications, optimization of operating parameters and use of bed additive/catalyst/sorbent (e.g. dolomite, etc.) [23]–[26]. From the gasifiers and parameters paragraphs it can be deducted the modifications (different reactor) and optimization (different parameters) methods. Regarding the catalyst more used in the TAR reduction, they are Ni-based catalysts, calcined dolomites, magnetite, and olivine [23]. The catalysts reduce TAR production and influence the gas composition. The use of catalytically materials during biomass gasification promotes the char gasification, changes the product gas composition and reduces the tar yield. Dolomite is the most popular and mostly studied in-bed additive [27]. Corella et al. [28] reported that the use of calcined dolomite inside the gasifier could decrease the TAR amount from 6.5 (without dolomite) to 1.3 %wt. An alternative can be olivine that is advantageous in terms of its attrition resistance over that of dolomite. Rapagnà et al. [16] investigated the catalytic activity of olivine and observed a TAR reduction (more than 90%). Another catalysts very used are the Ni-based catalysts. The major problem with Ni-based catalysts is fast deactivation due to carbon deposition on the catalyst, but these problems can be avoided increasing the temperature.

Thus introducing a catalyst in the bed material during gasification there are a change in product gas distribution, a decrease in TAR amount, an increase in hydrogen and CO_2 production, and a decrease of CO.

6. Power production technologies

The power production in the small scale biomass gasification plants is almost totally made via Internal Combustion Engines (ICE). There are few new realizations by means of micro Gas Turbines (mGT). Fuel cells (FC) or combined/hybrid mGT/FC power plants still are in the development stage, thus the power plant data are only theoretical. In this chapter realized and simulated literature power plant data are summarized in terms of gasifier typology, gasifying agent, clean up system, biomass, electrical and cogeneration efficiencies and capital cost. For a better comprehension, some of the reported parameters need explanation. In particular the gasification cold gas efficiency η_{chem} gives information about the efficiency of the gasification process and is defined earlier in equation (1). The overall system electrical efficiency η_{el} is defined as:

$$\eta_{el} = \frac{P_{out} - P_{aux}}{(Input\ biomass)_{LHV}} = \frac{P_{net}}{(Input\ biomass)_{LHV}} \tag{3}$$

P_{out} represents the electrical power output of the system (as sum of the power produced by the different technologies), while P_{aux} represent the power required by some of the system components, such as compressors, pumps, blowers, electrical generator, etc., if present. So P_{net} represents the effective electrical power that the system can generate. However in most cases and especially in plants that use ICE for power production the term P_{aux} is usually considered negligible by some authors, so the overall efficiency is simply defined as:

$$\eta_{el} = \frac{P_{out}}{(Input\ biomass)_{LHV}} = \eta_{chem} \cdot \eta_{mec} \cdot \eta_{gen} \tag{4}$$

where η_{mec} is the power producer mechanical efficiency and η_{gen} the efficiency of the electric generator. Furthermore the analysis provides other important information such as work temperature, fuel utilization factor (U_f) and current density (J) for SOFC and pressure ratio and Turbine Inlet Temperature (TIT) for mGT. Another important parameter is the combined heat and power efficiency η_{CHP}, defined as follows:

$$\eta_{CHP} = \frac{P_{out} - P_{aux} + Q_{useful}}{(Input\ biomass)_{LHV}} \tag{5}$$

where Q_{useful} means the net quantity of heat that can be used for cogeneration. ICE represent one of the first attempts to produce electricity from gasification producer gas because of their well-known technology and reliability. The quality of producer gas as a fuel is considerably poorer compared to gasoline and natural gas. Hence engines require certain design modifications to be carried out in order to be able to run on producer gas [29]. Spark ignition and diesel engines (eventually with a small fraction of diesel in a dual-fuel operation [30]) are the most used ones. Hasler and Nussbaumer indicate that the allowed particle and tar concentration in producer gas for satisfactorily ICE operation must be less than 50 mg/Nm³ and 100 mg/Nm³, respectively. The gas quality requirements described in the literature should be interpreted with caution since the type of the engine used in tests and its design features play an important role [31]. For ICE the majority of examples deals with realized plants (both experimental and commercial), instead of simulated ones. In particular there has been extensive experience of such systems around the world from 10 to 500 kWe [32]. Warren et al. [33], for example, studied and realized a 30 kW$_e$ farm-size wood-chips power pilot plant using a spark ignition engine and obtaining a global electrical efficiency of about 20%. A similar work was carried out by Lee et al. [34], who experimented a spark ignition engine (Ford DSG423) without any special modification, fed by the syngas produced from gasification of different feedstock in a DD at 800°C. Pine, red oak, horse manure and cardboard gave different electrical outputs and efficiencies with maximum values of 13.10 kW$_{el}$ for red oak and 23% for pine respectively. Wu et al. [35] gave a detailed overview of the small scale gasification plants situation in China. In particular a 200 kW$_e$ DD and a 1000 kW$_e$ CFB, using rice hull as feedstock and ICE as power producer, have been taken as representative models. The results of the investigation proved that biomass gasification systems are more affordable compared to the small-scale coal-fired power stations (with a lower specific cost of about 50% for the 1000 KW$_e$ system) and stated that electricity cost depends mainly on biomass cost. The description was improved by Zhou et al. [36] that analyzed the systems

realized by the Tianyan Green Energy Development and the Guangzhou Institute of Energy Conversion (GIEC). Tianyan developed biomass gasification systems with engine generators with capacities from 140 to 1000 kW_e. Two types of gasifiers have been adopted for gas production: DD (TYG-900B) for 200 kW_e gas engine unit capacity and below, and FB (TYL-1800–TYL-4500) for 400 kW_e and above. GIEC developed CFB with reformed diesel engines for 200-1200 kW_e capacities. Global efficiency reached 15-16% for Tianyan plants and 15% to 20% for GIEC ones. Dasappa et al. [30] reported the operational experience from a 100 kW_e biomass power plant as part of the Biomass Energy for Rural India program. In that case 18% global efficiency with a DD fed by air was reached. Tables 3 and 4 summarize, respectively, the most important ICE and mGT/ SOFC power plants data.

Table 3 ICE power plants data

Gasifier type	Gasif. Temp.	Oxydant	Clean-up system	Biomass type	Biomass LHV	Syngas LHV	η_{CHP}	P_{out} (P_{net})	η_{el}	Cost	REF
-	°C	-	-	-	MJ/kg	MJ/kg (MJ/Nm³)	%	kW_{el}	%	USD/kW_{el}	-
DD	N.A.	Air	Cold	Wood-chips	18	N.A.		30,0	20,0	N.A.	[33]
DD	800	Air	Cold	Pine	19,38	4,53	82,0	11,7	23,0	N.A.	[34]
				Red Oak	18,72	5,06	84,6	13,1	20,6	N.A.	
				Horse manure	18,14	5,22	84,4	10,1	21,3	N.A.	
				Cardboard	17,09	4,21	81,7	9,6	15,8	N.A.	
DD	N.A.	Air	Water scrubber	Rice hull	N.A.	(3.8-4.6)	50,0	200,0	12,5	330	[35]
CFB	775-940			Rice hull	N.A.	(4.6-6.3)	67 -75	1000,0	17,0	367	
DD	N.A.	Air	Water scrubber	Agro-forestry residues	14	4,8	N.A.	200,0	15,0	N.A.	[36]
CFB	N.A.				14	4,8	N.A.	1000,0	16,0	N.A.	
DD	N.A.	Air	Cold	Wood	N.A.	N.A.	N.A.	100 (85 ± 6)	18,0	N.A.	[30]

Table 4 mGT and SOFC power plants data

Power unit	SOFC Temp. (TIT)	J/U_f (Pres. ratio)	Gasif. type	Gasif. Temp.	Oxydant	Clean-up system	Biomass type	P_{out} (P_{net})	η_{CHP}	η_{el}	Cost	REF
-	°C	J/m²-	-	°C	-	-	-	kW_{el}	%	%		-
SOFC	900	3774/0.75						(170.3)	62.3	20.0	N.A.	
SOFC/mGT	900	4280/0.85 (4)	FB	807	Air	Hot	Olive kernel	(349.9)	58.1	40.6	N.A.	[41]
mGT	N.A.	(4)						(225.7)	70.7	26.1	N.A.	
mGT	(900)	(3.7)					Wood chips (beech + oak)	(140.1)	76.1	28.1	N.A.	[42]
SOFC	800	3000/0.85	DD	800	Air/steam	Cold		(181.5)	79.7	36.4	N.A.	
SOFC/mGT	800 (697)	3000/0.85(2.5)						(251.0)	79.7	50.3	N.A.	
SOFC/mGT	700-800 (950)	0.65-0.8 (4.5)	FB	820	Steam/O_2	Hot	Wood chips	(412-428)	N.A.	36-44	N.A.	[14]
SOFC	850	0.5	DD	600	Air	Cold	N.A.	200 (122.1)	33.9	20.8	2600 £/kW	[39]
	850	0.5	FB	900		Hot		200 (119.9)	59.6	22.6	2900 £/kW	
SOFC/mGT	(1000)	2500/0.85 (6)	DD	800	Air	Hot	N.A.	100 (88.47)	72.3	53.94	N.A.	[40]
SOFC	814	1750/0.56	CFB	850-900	SB 0.41 Steam ref.		Wood	(37.1)	N.A.	41.4	15000 $/kW	[47]
	816	1610/0.62			SB 0.41 Auto-th. ref.			(37.1)	N.A.	41.3		
SOFC/mGT	827 (1420)	3750/0.47			SB 0.40 Steam ref.			(61.3)	N.A.	68.4	8000 $/kW	
	827 (1000)	5080/0.56			SB 0.40 Auto-th. ref.			(50.2)	N.A.	56.0		

Higher efficiencies can be reached using mGT, SOFC or a combination of the two technologies as power production devices. Unfortunately for mGT and SOFC systems it is very difficult to find commercial small scale realized plants, so most of the found examples deals with experimental or complex simulated systems. Compared to processes that use ICEs as prime movers, mGT and SOFC require stricter limits about tars and particulate presence in the raw gas. For mGT tars are tolerated only in vapour form, while particulate limit depends on the size, ranging between 0,1 ppm with > 20 μm particles to 10 ppm with 4-10 μm ones [32]. Furthermore low level of HCl (< 0.5 ppm) and H_2S, SO_2 and sulfur compounds (< 1 ppm) are required [32]. For SOFC limits are even stricter. As a matter of fact tar molecules can potentially impact the SOFC in several ways, including the deactivation of the catalysts and the degradation of the fuel cells with carbon deposition. Moreover it has been suggested that, even at low ppmv levels, H_2S is adsorbed at active sites of the anode, thus inhibiting the fuel molecules from getting adsorbed and, in turn, affecting the fuel oxidation reactions, while at higher concentrations sulfur will react with nickel and cause irreversible damage. For example the presence of even 1 ppm of sulfur is likely to affect the performance of cells with Ni/YSZ anodes [37]. Also HCl can cause problems with SOFC operation. In particular it has to be removed before the gas is fed to a SOFCs because it can cause corrosion of system components and it can

react with catalysts like nickel-based ones and with components of the SOFC anodes, causing cell degradation [37]. Palma and Martin [38] studied six different system configurations for a fluidized bed gasifier fed by air and poultry litter and using a mGT (200 kW$_e$) as prime mover, with electrical efficiencies ranging between 26% and 33.5%. Instead Omosum et al. [39] investigated the integration of a SOFC with biomass gasification for the contemporary production of power and heat (CHP system), using a steady-state model developed in the gPROMS modelling tool. The comparison between a fixed bed downdraft gasifier with a cold clean up system and a fluidized bed gasifier with a hot one (catalyst in the bed material) in terms of power, efficiency and capital cost was analyzed. Results obtained from the simulation stated that the global efficiency for the hot process (22.6% electrical and 59.6% for the whole system) was higher than that for the cold process (20.8% electrical and 33.9% for the whole system) because of better heat management in the cleaning process and higher gasification temperature. Though the capital cost for the hot process was marginally higher (2900 £/kW$_e$ against 2600 £/kW$_e$), income earned from selling the extra heat produced may justify the additional cost. Aravind et al. [40] reported thermodynamic simulations with a 100 kW$_e$ power plant based on a fixed bed air-blown gasifier and a hybrid SOFC (with Nickel/Gadolinia Doped Ceria (Ni/GDC) anodes) – mGT system. The results obtained indicated that when gas cleaning is carried out at temperatures lower than gasification temperature, additional steam has to be added to raw gas in order to avoid carbon deposition. Base case results (gas cleaning temperature of 850°C) showed a net electrical power of 88.47 kW$_e$ with an electric efficiency of 53.94% and a total one of 72.30%. Fryda et al. [41] investigated on the combination of an air blown fluidized bed gasifier with a high temperature tubolar SOFC (100 m^2 stack active area) and/or mGT in a CHP system of less than 1 MW$_e$, which could operate near atmospheric pressure and at 4 bar, using AspenPlus^{TM} as simulation software. In particular a SOFC at atmospheric pressure (170 kW$_e$), a mGT at 4 bar (225 kW$_e$) and a SOFC+mGT at 4 bar (350 kW$_e$) configurations were simulated. Results showed respectively global electrical efficiencies of 20% (with SOFC current density (J) of 3774 J/m^2 and fuel utilization factor (U$_f$) of about 0.75%), 40.6% and 26.1% (with SOFC J = 4280 J/m^2 and U$_f$ = 0.85%). Bang-Møller et al. [42] worked on a similar simulation (using the simulation tool Dynamic Network Analysis (DNA)), but based on a 500 kW$_{th}$ fixed bed air steam blown gasification plant, scaled up from and validated by the 75 kW$_{th}$ Viking system developed at The Technical University of Denmark. In this case the mGT configuration (140 kW$_e$) provided a global electrical efficiency of 28% (with a T.I.T. of 900°C and a pressure ratio of 3.7); instead SOFC configuration efficiency reached 36.4% (with U$_f$ = 85% and J = 300 mA/cm^2 and at 800°C), higher than mGT one because of the SOFC better fuel conversion, finally, with the SOFC + mGT configuration (251 kW$_e$), using all of the heat produced, with a pressure ratio of 2.5 (and a TIT of 697°C) a global electrical efficiency of 50,3% was reached. Di Carlo et al. [14] simulated a SOFC + mGT system (by means of the CHEMCAD software) based on a bubbling fluidized bed gasifier fed by wood and a mix of steam and O$_2$-enriched air as gasifying agent. The analysis was based on a gasifier model that was developed by some of the authors in an earlier work [43]–[46]. A bundle of catalytic ceramic filter candles (UNIQUE system) in the upper part of the gasifier as clean-up system for both tar and sulphur compounds was used. The work demonstrated that the variation of the fuel utilization factor Uf (from 0.65 to 0.8), in spite of a strong decrease in mGT power output, makes the global system power increase from 412 kWe to 428 kWe. Moreover varying both the utilization factor and the percentage of oxygen purity in the air stream (from 0.25% to 0.95%) the global efficiency reaches values ranging between 36% to 44%, that is much higher than the one obtained burning the woodgas in internal combustion engines. Finally a sensitivity analysis confirmed that the highest efficiency is obtained using pure oxygen and steam as gasifying agents, but demonstrated that oxygen purity variation provokes maximum efficiency decrease of 2%, making economically questionable the adoption of complex and energy consuming air separation units. Morandin et al. [47] performed thermo-economic analysis of 9 different system configurations (with nominal power of less than 100 kW) as combinations of the Viking downdraf gasifier (VG) or a fast internally circulating fluidized bed one (FB), two different syngas reformers (steam and autothermal) and a fFC and a mGT (hybrid system) or a steam turbine (combined system) as power generating equipment. The system fuel input consisted of 40 kg/h of woody biomass at 50% moisture (but dried before entering the reactor). The different plant configurations were optimized following the maximization of the global electrical efficiency and minimization of the capital investment simultaneously. It stated that the choice of auto-thermal reforming instead of steam reforming can decrease the system costs, but only up to a certain level, after which the benefits of steam reforming on thermodynamics, recovering high temperature heat into hydrogen as chemical storage, let the system reach higher efficiency. Best configuration gave a global electrical power of about 37 kW$_e$ and an efficiency of 41%, with specific

cost of about 15000 \$/kW$_{el}$ (2010 dollars), low if compared to the Viking system. Thermo-economic analysis of the combined mode confirmed the higher performances of the FB and the steam reformer, with a maximum power output of 52 kW$_{el}$, a global electrical efficiency of about 58% and a cost of more than 11000 \$/kW$_{el}$. Finally the hybrid configuration gave the best results with a system net power of 61 kW$_{el}$, a global efficiency of 68% and a specific cost of 8000 \$/kW$_{el}$.

7. Conclusions

Small biomass gasification power plants provide a competitive way to convert diverse, highly distributed and low-value lignocellulosic waste biomass to syngas for combined heat and power generation. Biomass gasification power plants based on downdraft gasifier and ICE has been successfully commercialized. The electrical and cogeneration efficiencies are about 20% and 80% with a global capital cost of about 500-1000 €/kWe. Bubbling fluidized bed gasification with steam, indirect heat supply and primary conditioning method with catalysts could provide a promising way to improve the syngas yield and quality. In this way the system is more reliable (more annual operating hours, more different typologies of biomass to be used, more load variation, etc.), the electrical efficiency can increase to about 40% but the global capital cost, mostly due to the early development stage, increase to about 10000-15000 €/kWe (cost of about 1000 €/kWe can be envisaged when the technologies, i..e fluidized bed, catalyst, mGT-fuel cells, will be widely developed). However, more research is needed to improve syngas quality for its commercial uses in a high energy-efficient heat and power generator such as gas turbines or fuel cells, especially in developing novel catalysts and supporting materials to improve the selectivity, activity, productivity and economy of a catalytic process for syngas cleaning and downstream utilizations.

References

[1]   E. Bocci, A. Di Carlo, and D. Marcelo, "Power plant perspectives for sugarcane mills," *Energy*, vol. 34, no. 5, pp. 689–698, 2009.
[2]   D. Monarca, M. Cecchini, and A. Colantoni, "Plant for the production of chips and pellet: technical and economic aspects of an case study in the central Italy," in *Computational Science and Its Applications-ICCSA 2011*, Springer, 2011, pp. 296–306.
[3]   F. Orecchini and E. Bocci, "Biomass to hydrogen for the realization of closed cycles of energy resources," *Energy*, vol. 32, no. 6, pp. 1006–1011, 2007.
[4]   F. Orecchini, E. Bocci, F. Zuccari, and A. Santiangeli, "Elettricita da fonti energetiche rinnovabili. Le potenzialita dell'Italia," *TERMOTECNICA-MILANO-*, vol. 58, no. 1, pp. 81–88, 2004.
[5]   L. Pari, "Energy production from biomass: the case of Italy," *Renewable energy*, vol. 22, no. 1, pp. 21–30, 2001.
[6]   E. Bocci, A. Di Carlo, L. Vecchione, M. Villarini, M. De Falco, and A. Dell'Era, "Technical-Economic Analysis of an Innovative Cogenerative Small Scale Biomass Gasification Power Plant," in *Computational Science and Its Applications–ICCSA 2013*, Springer, 2013, pp. 256–270.
[7]   E. Bocci, M. Villarini, A. Caffarelli, and A. D'Amato, *SISTEMI A BIOMASSE: PROGETTAZIONE E VALUTAZIONE ECONOMICA*. Torino: Maggioli Editore, 2011.
[8]   D. Monarca, A. Colantoni, M. Cecchini, L. Longo, L. Vecchione, M. Carlini, and A. Manzo, "Energy Characterization and Gasification of Biomass Derived by Hazelnut Cultivation: Analysis of Produced Syngas by Gas Chromatography," *Mathematical Problems in Engineering*, vol. 2012, Nov. 2012.
[9]   M. Carlini, S. Castellucci, S. Cocchi, and A. Manzo, "Waste Wood Biomass Arising from Pruning of Urban Green in Viterbo Town: Energy Characterization and Potential Uses," in *Computational Science and Its Applications–ICCSA 2013*, Springer, 2013, pp. 242–255.
[10]   Energy research Centre of the Netherlands, "Phyllis database for biomass and waste." [Online]. Available: http://www.ecn.nl/phyllis2. [Accessed: 02-May-2013].
[11]   L. Wang, C. L. Weller, D. D. Jones, and M. A. Hanna, "Contemporary issues in thermal gasification of biomass and its application to electricity and fuel production," *Biomass and Bioenergy*, vol. 32, no. 7, pp. 573–581, 2008.
[12]   L. Vecchione, M. Moneti, E. Bocci, A. D. Carlo, and P. Foscolo, "Steam Gasification of Pine Wood in a Fluidized Bed Reactor: Model Development and Validation at Different Operative Conditions," *21st European Biomass Conference and Exhibition,*, no. DOI 10.5071/21stEUBCE2013–2CV.3.35, pp. 841–848, 2013.
[13]   J. Herguido, J. Corella, and J. Gonzalez-Saiz, "Steam gasification of lignocellulosic residues in a fluidized bed at a small pilot scale. Effect of the type of feedstock," *Industrial & engineering chemistry research*, vol. 31, no. 5, pp. 1274–1282, 1992.
[14]   A. Di Carlo, D. Borello, and E. Bocci, "Process simulation of a hybrid SOFC/mGT and enriched air/steam fluidized bed gasifier power plant," *International Journal of Hydrogen Energy*, vol. 38, no. 14, pp. 5857–5874, May 2013.
[15]   J. Gil, M. P. Aznar, M. A. Caballero, E. Francés, and J. Corella, "Biomass Gasification in Fluidized Bed at Pilot Scale with Steam−Oxygen Mixtures. Product Distribution for Very Different Operating Conditions," *Energy Fuels*, vol. 11, no. 6, pp. 1109–1118, Nov. 1997.
[16]   S. Rapagna, N. Jand, A. Kiennemann, and P. U. Foscolo, "Steam-gasification of biomass in a fluidised-bed of olivine particles," *Biomass and Bioenergy*, vol. 19, no. 3, pp. 187–197, 2000.
[17]   G. J. Corella, M. P. Aznar, and M. A. Caballero, "Biomass gasification in atmospheric and bubbling fluidized bed: effect of the type of

E. Bocci et al. / Energy Procedia 45 (2014) 247 – 256

gasifying agent on the product distribution," *Biomass and Bioenergy*, vol. 17, no. 5, pp. 389–403, 1999.

[18] R. Warnecke, "Gasification of biomass: comparison of fixed bed and fluidized bed gasifier," *Biomass and Bioenergy*, vol. 18, no. 6, pp. 489–497, Jun. 2000.

[19] D. Kunii and O. Levenspiel, "Fluidized reactor models. 1. For bubbling beds of fine, intermediate, and large particles. 2. For the lean phase: freeboard and fast fluidization," *Ind. Eng. Chem. Res.*, vol. 29, no. 7, pp. 1226–1234, Jul. 1990.

[20] Q. Yu, C. Brage, G. Chen, and K. Sjöström, "Temperature impact on the formation of tar from biomass pyrolysis in a free-fall reactor," *Journal of Analytical and Applied Pyrolysis*, vol. 40–41, pp. 481–489, May 1997.

[21] I. Narváez, A. Orío, M. P. Aznar, and J. Corella, "Biomass Gasification with Air in an Atmospheric Bubbling Fluidized Bed. Effect of Six Operational Variables on the Quality of the Produced Raw Gas," *Ind. Eng. Chem. Res.*, vol. 35, no. 7, pp. 2110–2120, Jan. 1996.

[22] C. M. Kinoshita, Y. Wang, and J. Zhou, "Tar formation under different biomass gasification conditions," *Journal of Analytical and Applied Pyrolysis*, vol. 29, no. 2, pp. 169–181, 1994.

[23] L. Devi, K. J. Ptasinski, and F. J. Janssen, "A review of the primary measures for tar elimination in biomass gasification processes," *Biomass and Bioenergy*, vol. 24, no. 2, pp. 125–140, 2003.

[24] A. Di Carlo, E. Bocci, F. Zuccari, and A. Dell'Era, "Numerical Investigation of Sorption Enhanced Steam Methane Reforming Process Using Computational Fluid Dynamics Eulerian- Eulerian Code," *Industrial & Engineering Chemistry Research*, vol. 49, no. 4, pp. 1561–1576, 2010.

[25] A. D'Orazio, A. Di Carlo, N. Dionisi, A. Dell'Era, and F. Orecchini, "Toluene steam reforming properties of CaO based synthetic sorbents for biomass gasification process," *International Journal of Hydrogen Energy*, 2013.

[26] M. Sisinni, A. Di Carlo, E. Bocci, A. Micangeli, and V. Naso, "Hydrogen-Rich Gas Production by Sorption Enhanced Steam Reforming of Woodgas Containing TAR over a Commercial Ni Catalyst and Calcined Dolomite as CO2 Sorbent," *Energies*, vol. 6, no. 7, pp. 3167–3181, 2013.

[27] S. Rapagnà, N. Jand, and P. U. Foscolo, "Catalytic gasification of biomass to produce hydrogen rich gas," *International Journal of Hydrogen Energy*, vol. 23, no. 7, pp. 551–557, Jul. 1998.

[28] J. Corella, A. Orio, and J.-M. Toledo, "Biomass gasification with air in a fluidized bed: Exhaustive tar elimination with commercial steam reforming catalysts," *Energy & Fuels*, vol. 13, no. 3, pp. 702–709, 1999.

[29] J. D. Martínez, K. Mahkamov, R. V. Andrade, and E. E. Silva Lora, "Syngas production in downdraft biomass gasifiers and its application using internal combustion engines," *Renewable Energy*, vol. 38, no. 1, pp. 1–9, Feb. 2012.

[30] S. Dasappa, D. N. Subbukrishna, K. C. Suresh, P. J. Paul, and G. S. Prabhu, "Operational experience on a grid connected 100 kWe biomass gasification power plant in Karnataka, India," *Energy for Sustainable Development*, vol. 15, no. 3, pp. 231–239, Sep. 2011.

[31] P. Hasler and T. Nussbaumer, "Gas cleaning for IC engine applications from fixed bed biomass gasification," *Biomass and Bioenergy*, vol. 16, no. 6, pp. 385–395, Jun. 1999.

[32] A. V. Bridgwater, "The technical and economic feasibility of biomass gasification for power generation," *Fuel*, vol. 74, no. 5, pp. 631–653, May 1995.

[33] T. J. B. Warren, R. Poulter, and R. I. Parfitt, "Converting biomass to electricity on a farm-sized scale using downdraft gasification and a spark-ignition engine," *Bioresource Technology*, vol. 52, no. 1, pp. 95–98, 1995.

[34] U. Lee, E. Balu, and J. N. Chung, "An experimental evaluation of an integrated biomass gasification and power generation system for distributed power applications," *Applied Energy*, vol. 101, pp. 699–708, Jan. 2013.

[35] C. . Wu, H. Huang, S. . Zheng, and X. . Yin, "An economic analysis of biomass gasification and power generation in China," *Bioresource Technology*, vol. 83, no. 1, pp. 65–70, May 2002.

[36] Z. Zhou, X. Yin, J. Xu, and L. Ma, "The development situation of biomass gasification power generation in China," *Energy Policy*, vol. 51, pp. 52–57, Dec. 2012.

[37] P. V. Aravind and W. de Jong, "Evaluation of high temperature gas cleaning options for biomass gasification product gas for Solid Oxide Fuel Cells," *Progress in Energy and Combustion Science*, vol. 38, no. 6, pp. 737–764, Dec. 2012.

[38] C. Font Palma and A. D. Martin, "Model based evaluation of six energy integration schemes applied to a small-scale gasification process for power generation," *Biomass and Bioenergy*, vol. 54, pp. 201–210, Jul. 2013.

[39] A. . Omosun, A. Bauen, N. . Brandon, C. . Adjiman, and D. Hart, "Modelling system efficiencies and costs of two biomass-fuelled SOFC systems," *Journal of Power Sources*, vol. 131, no. 1–2, pp. 96–106, May 2004.

[40] P. V. Aravind, T. Woudstra, N. Woudstra, and H. Spliethoff, "Thermodynamic evaluation of small-scale systems with biomass gasifiers, solid oxide fuel cells with Ni/GDC anodes and gas turbines," *Journal of Power Sources*, vol. 190, no. 2, pp. 461–475, May 2009.

[41] L. Fryda, K. D. Panopoulos, and E. Kakaras, "Integrated CHP with autothermal biomass gasification and SOFC–MGT," *Energy Conversion and Management*, vol. 49, no. 2, pp. 281–290, Feb. 2008.

[42] C. Bang-Møller and M. Rokni, "Thermodynamic performance study of biomass gasification, solid oxide fuel cell and micro gas turbine hybrid systems," *Energy Conversion and Management*, vol. 51, no. 11, pp. 2330–2339, Nov. 2010.

[43] A. Di Carlo, E. Bocci, and V. Naso, "Process simulation of a SOFC and double bubbling fluidized bed gasifier power plant," *International Journal of Hydrogen Energy*, vol. 38, no. 1, pp. 532–542, Jan. 2013.

[44] A. Di Carlo, E. Bocci, and A. Dell'Era, "Comparison by the use of numerical simulation of a MCFC-IR and a MCFC-ER when used with syngas obtained by atmospheric pressure biomass gasification," *International Journal of Hydrogen Energy*, vol. 36, no. 13, pp. 7976–7984, 2011.

[45] F. Orecchini, E. Bocci, and A. Di Carlo, "Process simulation of a neutral emission plant using chestnut's coppice gasification and molten carbonate fuel cells," *Journal of fuel cell science and technology*, vol. 5, no. 2, 2008.

[46] F. Orecchini, E. Bocci, and A. Di Carlo, "MCFC and microturbine power plant simulation," *Journal of power sources*, vol. 160, no. 2, pp. 835–841, 2006.

[47] M. Morandin, F. Maréchal, and S. Giacomini, "Synthesis and thermo-economic design optimization of wood-gasifier-SOFC systems for small scale applications," *Biomass and Bioenergy*, vol. 49, pp. 299–314, Feb. 2013.