A review of available and emerging technologies for the production of substitute natural gas via gasification of biomass

Rosa Domenichini, Luca Mancuso, Fabio Ruggeri, Juha Palonen

Biomass gasification can provide an economically viable system for producing gaseous bio-fuels. This route can benefit from all the advantages of natural gas, that is, in addition to a well-established infrastructure in many parts of the world, it can be used as an alternative fuel in the transportation sector and allow power plants to meet very high efficiency targets. Furthermore, there are countries that import natural gas, while having a great domestic availability of biomass.

The main purpose of this paper is to investigate biomass gasification for the co-production of power and substitute natural gas (SNG), which can be distributed by using the existing electricity and natural gas grid infrastructures, respectively.

Foster Wheeler’s fluidized-bed gasification technology and its methanation technology (the VESTA process) are presented in this work. The process chain necessary for the thermo-chemical production of SNG from biomass is described. Different alternatives are identified for the main involved technological steps such as tar removal processes, syngas conditioning and cleaning, with the main goal of designing a performing and reliable plant, based on the use of industrial and recognized technologies.

Introduction

The gasification of biomass aimed at the production of SNG allows a gaseous fuel to be obtained from a source of renewable carbon. The biomass types are generally considered neutral as regards the greenhouse effect because the carbon dioxide is absorbed by plants in the growth phase, through the process of photosynthesis. The low content of sulfur, ash

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Juha Palonen is Product Manager of Gasifiers for Foster Wheeler Energia Oy, Department of Research & Development, at Varkaus Boiler Works, Finland. He joined Foster Wheeler in 1989, starting at the Karhula R&D Center, Finland. Since 1993, he has worked in the area of fluidized bed gasification. He has been involved in the mathematical modeling of CFB processes, and in the development work of e.g. RDF combustion, pressurized biomass gasification (IGCC cycle) and atmospheric CFB gasification of various fuels in pilot plant, demonstration plant and commercial plant scale. He is currently involved in oxygen-steam blown gasification processes for BtL, SNG, etc applications.

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and other pollutants also results in a limited production of solid and liquid waste streams. Among the different biomass types, suitable for processing via gasification, the most common are forest and wood industry residue, wood chips, agricultural byproducts and waste food.

**Process Scheme and Technology Review**

SNG can be produced from biomass by using different plant configurations, depending on the gasification technology selected. The major stages of the production process are shown in Figure 1.

**Gasification**

Gasification is the initial stage of the SNG production process from biomass, generating synthesis gas (syngas) that is mainly composed of carbon monoxide and hydrogen. The syngas produced in the gasification step is then appropriately treated in the downstream process units, before being used for the production of SNG.

Amongst the different gasification technology types, the entrained flow gasifier is the most well-known technology. Nevertheless, its specific experience with biomass gasification at large scale is confined to co-gasification with other fuels, while pure biomass gasification is generally limited to pilot plant or small-scale demonstration plants. Direct biomass gasification in an entrained flow gasifier might require specially-designed feeding systems which could result in operational difficulties and increased investment cost. Therefore, pre-treatment of the biomass would be considered, in order to generate a feedstock with the same characteristics as a conventional solid or liquid fuel. In this respect, two different processes are suitable for treating the feedstock, namely torrefaction and pyrolysis. However, both these processes have not reached a level of maturity sufficient to justify their application in large-scale commercial plants.

Another well-proven technology is the fluidized-bed gasifier, whose major advantage is the possibility to directly feed the biomass to the gasifier, after a conventional drying process. Indeed, when biomass or waste fuels are considered for combustion, fluidized-bed technology is the common choice: bubbling fluidized-bed boilers (BFB) have often been favored in small-scale industrial applications, while circulating fluidized-bed boilers (CFB) have been proven to be more advantageous in larger applications.

Among other factors, the operating temperature is of major importance. In fact, while the entrained flow gasifier operates around 1,400°C, the gasification in a fluidized-bed reactor is normally carried out at about 900°C, which guarantees significantly higher methane content in the syngas. On the other hand, this technology leads to the formation of organic compounds (tar) in the syngas (up to $10^4$ mg/Nm$^3$), which implies the need to use treatment units in the downstream stages of gasification. In addition, the biggest challenges in biomass-fired CFBs are the increased risks for agglomeration, fouling, and corrosion for which Foster Wheeler has developed its own characterization procedures and methods.

During the past 30 years, Foster Wheeler has designed more than 360 CFB boilers ranging from 7MWth to nearly 1,000 MWth; of these, over 50 are designed for biomass (or bio-mix). The following sections provide a deeper description of the Foster Wheeler experience in gasification.

**Foster Wheeler air-blown CFB gasification**

The development of atmospheric air-blown gasification technology and gasification modeling tools continues at Foster Wheeler, especially for the large-scale applications (around 150 MWth), as shown in Table 1. This development work is a follow-on to the very successful commercial-scale demonstration of the technology, for
example in the Lahti gasification plant in Finland.

The Lahti gasification plant is a 40–70 MW$_{th}$ atmospheric unit, which consists of a CFB gasifier, air preheater, gas duct to the burners and two product gas burners in a pulverized coal-fired boiler. The whole concept, including the product gas burners, was designed and built by Foster Wheeler. The flow scheme of the Lahti gasification plant and examples of the fuels are shown in Figure 2.

Based on the successes of the earlier projects and evaluation of the future needs, Foster Wheeler has been developing a larger-scale gasification concept for converting various different types of fuels e.g. biomass, agro-biomass, waste-based fuels, etc, into syngas, either to be co-combusted directly in existing boilers or to be cleaned and combusted individually in a stand-alone/greenfield plant.

The company has also designed CFB gasification plants for over 100 MW$_{th}$ applications for various wood-based biomass and waste fuels such as in-origin classified recycled fuel (REF) and refuse-derived fuel (RDF). A preliminary layout model of the large-scale gasification plant is shown in Figure 3.

Foster Wheeler pressurized CFB gasification development

The world’s first complete IGCC power plant, which utilizes wood as fuel, was built in Sweden in the early 1990s (Figure 4). The demonstration plant is located in Värnamo and the technology used in the power plant is based on gasification in a pressurised circulating fluidised-bed gasifier. The technology was developed by Foster Wheeler in cooperation with the former Sydkraft AB.

The start-up phase was completed during spring 1996 and, following that, a successful demonstration programme was launched, which was continued until June 2000. The accumulated operating experience amounts to about 8,500 hours of gasification runs and about 3,600 hours of operation as a fully integrated plant by the end of 1999.

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**Table 1. Foster Wheeler atmospheric gasifier references**

<table>
<thead>
<tr>
<th>Customer</th>
<th>Size MW</th>
<th>Fuel</th>
<th>Application</th>
<th>Year</th>
</tr>
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<tbody>
<tr>
<td>Hans Ahistrom Laboratory, Finland*</td>
<td>3</td>
<td>Misc.</td>
<td>Test unit</td>
<td>1981</td>
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<tr>
<td>Oy W.Schauman Ab, Finland*</td>
<td>35</td>
<td>Bark, saw dust</td>
<td>lime kiln fuel</td>
<td>1983</td>
</tr>
<tr>
<td>Norrsundet Bruks Ab, Sweden*</td>
<td>25</td>
<td>Bark</td>
<td>lime kiln fuel</td>
<td>1984</td>
</tr>
<tr>
<td>Assi Karlsborg, Sweden*</td>
<td>27</td>
<td>Bark</td>
<td>lime kiln fuel</td>
<td>1984</td>
</tr>
<tr>
<td>Portucel, Rodao, Portugal*</td>
<td>15</td>
<td>Bark</td>
<td>lime kiln fuel</td>
<td>1985</td>
</tr>
<tr>
<td>Kemira Oy, Vuorkemia, Finland</td>
<td>Coal, peat</td>
<td>Test unit, clean gas</td>
<td>1986</td>
<td></td>
</tr>
<tr>
<td>Lahden Lampovoima Oy, Finland</td>
<td>40-70</td>
<td>Biofuels</td>
<td>Hot raw gas to boiler</td>
<td>1997</td>
</tr>
<tr>
<td>Corenso United Ltd, Finland</td>
<td>40</td>
<td>Aluminous plastic waste</td>
<td>Cyclone cleaned gas to boiler</td>
<td>2000</td>
</tr>
<tr>
<td>Electrabe, Belgium</td>
<td>50</td>
<td>Biofuels</td>
<td>Hot raw gas to boiler</td>
<td>2002</td>
</tr>
<tr>
<td>NSE Biofuels Ltd, Finland</td>
<td>12</td>
<td>Biofuels</td>
<td>Lime kiln fuel</td>
<td>2008</td>
</tr>
</tbody>
</table>

* = supplied by A Ahistrom Corp.

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**Foster Wheeler oxygen-steam-blown gasification and gas cleaning development**

**Finnish approach**

The development of the ultra-clean gas technology for future applications was launched in 2004 in Finland as a publicly funded project with industrial partners. In this first stage of development work, Foster Wheeler was one of the biggest industrial partners in a project which was coordinated by VTT (Technical Research Center of Finland). The project consisted of small-scale experiments, process evaluations and design, construction and operation of a 0.5 MW process demonstration unit at VTT. The PDU test runs were started in 2006 and the first part of the development path was concluded in 2007.

**The Biomass-to-Liquids (BtL) demonstration plant**

The second step in the development path was a long-
term demonstration at a larger scale. Together with Foster Wheeler, Finnish joint venture NSE Biofuels built a demonstration plant in Varkaus, Finland, to demonstrate long-term gas production and gas cleaning to meet the requirements of Fischer-Tropsch (FT) synthesis.

Gas for the gas cleaning test plant was produced in an atmospheric oxygen-steam-blown 12 MWth CFB gasifier, which also supplied, and still supplies today as an air-blown unit, gas for the lime kiln of the Stora Enso pulp and paper mill. The whole process chain of the plant is shown in Figure 5.

Foster Wheeler supplied the 12 MWth CFB gasifier with auxiliaries and some of the main equipment for the gas cleaning plant: gas coolers, hot gas filters, ash handling systems and the scrubber. Foster Wheeler also executed the majority of the process design, including the control system.

Experimental Studies

The test runs were carried out to optimize the gasifier process parameters for producing good quality raw gas for the follow-up process. Tars, light hydrocarbons, HCN, NH₃, H₂S and COS and fly ash/particulates were analyzed from the raw gas, as well as the main components of gas, CO, CO₂, H₂, CH₄ and H₂O. Carbon conversion of the gasifier was also determined. Test runs included testing at different gasification temperatures ranging from 860 to 940 °C and different oxygen/steam ratios. The oxygen content of the fluidizing agent into the wind box was varied between 23% and 50%-w, typical value being around 45 %-w. The fuel consisted of different types of

| Power / heat generation | 6 MWe/9MWth |
| Fuel input | 18 MWfuel (85%ds) |
| Fuel | Wood chips. (Several other fuels were tested with good results.) |
| Net electrical efficiency (LCV) | 32% |
| Total net efficiency (LCV) | 83% |
| Gasification pressure / temperature | 18 bar (g) / 950 °C |

Fig 4. Varnamo biomass IGCC demonstration plant (Foster Wheeler W scope) and key process data

Fig 5. Process chain of the NSE demo plant
woody biomass: wood chips, first-felling wood, bark and forest residues.

The key objectives of the gas cleaning test runs in Foster Wheeler’s scope were to demonstrate the performance of the gas coolers and the hot gas filters in long-term operation and to determine the design basis for this equipment.

The cumulative operation hours of the oxygen-steam gasification exceeded 9,000 by the beginning of June 2011 and for the slip-stream gas cleaning plant the operation hours were more than 5,500 hours.

As an example, the main raw gas components of the oxygen-steam gasification during a test run in spring 2011 were CO₂, H₂ and CO, which together covered around 75-80% of the total dry gas.

**Tar Removal**

The definition of tar is unfortunately not standard. According to the designation used during the IEA Gasification Task meeting in 1999, for example, tars are “organic compounds with boiling temperature higher than that of benzene” (80°C). As a reference, the syngas from a fluidized-bed gasifier can contain tar with a boiling temperature as high as 350°C. On top of this categorization, tar can also be split into “light tar” and “heavy tar”, based on the molecular weight being lower or greater than about 200 g/mol. Some examples of tar are: pyridine, toluene, anthracene, naphthalene, and pyrene.

The presence of tar in the syngas exiting the gasifier is one of the potential problems of primary concern for the gasification of biomass, regardless of whether the purpose is power generation or chemical production. In fact, the presence of organic compounds entails significant problems associated with the fouling of some equipment (heat exchange surfaces, filters, adsorbent, etc.) and condensate contamination during the synthesis gas cooling process.

The formation of tar appears to be significant for temperatures below 1,000°C and the quantity and composition mainly depends on the feedstock characteristics, the conditions of pyrolysis in the gasifier, and the secondary reactions in the gas phase.

Foster Wheeler derived from its experience in fluidized beds, including nearly 10,000 fuel samples and over 1,000 tests in about 150 CFB units, semi-empirical computer tools (probability models) capable of generating different probability indices for agglomeration, fouling, and corrosion. Although the models are based on some simplifying assumptions, the results have proven to align well with the behavior of commercially operating CFBs.

Tar can be removed through specific processes downstream of the gasifier, such as water scrubbing, oil scrubbing, thermal cracking, and catalytic cracking. Table 2 summarizes the main advantages and disadvantages of

<table>
<thead>
<tr>
<th>Process</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aqueous Scrubbing</td>
<td>• Good efficiency</td>
<td>• Tars pass from gas to liquid phase</td>
<td>• Light tars in the clean syngas</td>
</tr>
<tr>
<td></td>
<td>• Smooth and trouble-free operation</td>
<td>• High Capex for WWT</td>
<td></td>
</tr>
<tr>
<td>Thermal Cracking</td>
<td>• Complete removal</td>
<td>• Soot formation</td>
<td>• None</td>
</tr>
<tr>
<td></td>
<td>• Chemical energy remains in syngas</td>
<td>• High Capex</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Low thermal efficiency</td>
<td>(product used to provide heat)</td>
<td></td>
</tr>
<tr>
<td>Catalyst</td>
<td>• Potential complete removal</td>
<td>• Soot formation</td>
<td>• Coke formation racking and catalyst deactivation</td>
</tr>
<tr>
<td></td>
<td>• Chemical energy remains in syngas</td>
<td>• Catalyst consumption and cost</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Composition of product gas can be adjusted</td>
<td>• Catalyst disposal due to Ni</td>
<td></td>
</tr>
<tr>
<td>Oil Scrubbing</td>
<td>• Stability and availability</td>
<td>• Scrubber/Stripper to remove NH₃, HCL, H₂S</td>
<td>• Naphtalene in the clean syngas: test required</td>
</tr>
<tr>
<td></td>
<td>• Chemical energy remains in syngas (tars recycle)</td>
<td>• High level of filtration at high temperature</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Tar removal technology comparison
these tar removal technologies.

**Syngas Purification Process**

The purification of synthesis gas essentially consists of acid gas removal (H₂S, COS, HCN, NH₃, optionally CO₂, etc.) which can be achieved through physical or chemical absorption.

Additionally, residual components like benzene, toluene or naphthalene that have not been fully removed or decomposed in the previous steps should also be reduced down to acceptable levels for the downstream catalytic methanation (typically less than 5 ppm vol).

**Physical absorption systems**

A solvent’s absorption capacity is tied to Henry’s law and, therefore, is proportional to the partial pressure of the component to be removed. At a certain total pressure, the solvent’s circulation is then linked to the volume of gas processed.

The physical absorption process allows a hydrogen sulfide concentration in the exiting stream lower than one part per million on a volumetric basis to be reached. The selective removal of hydrogen sulfide at high rates typically forces the use of a refrigerating cycle in order to cool down the solvent sent back to the absorber. SELEXOL (UOP) and Rectisol (Linde/Lurgi) are examples of such technologies.

**Chemical absorption systems**

The absorption capacity of a chemical scrubbing process is related to the quantity of the active component in the solution. The solvent’s circulation is approximately proportional to the volume of acid gas to be removed and the regeneration is often achieved through a combination of depressurization and stripping.

The chemical absorption, which typically employs amine-based solvents, is able to lower the concentration of sulfur in the exiting stream down to few parts per million on a volumetric basis.

**Deep desulphurization**

The downstream catalytic processes are easily poisoned by sulfur, and therefore it should be reduced to ppb (parts per billion) level. The sulfur reduction from ppm to ppb is performed in a fixed-bed absorption process, acting as a non-regenerable guard bed before the SNG process.

**Methanation - The VESTA Process**

The most important step in the SNG production chain is represented by the methanation process, during which the carbon oxides and hydrogen are converted into methane in line with the following equilibrium reactions:

\[
\begin{align*}
CO + 3H_2 &= CH_4 + H_2O \\
CO_2 + 4H_2 &= CH_4 + 2 H_2O
\end{align*}
\]

These reactions are strongly exothermic and take place in a series of adiabatic fixed-bed catactyl reactors, with intermediate cooling.

In the conventional SNG processes the adjustment of the \((H_2:CO_2)/(CO+CO_2)\) ratio to a value of about 3 (stoichiometric) upstream of the methanation section is required. The exothermic nature of the reaction is controlled by recycling a substantial portion (typically above 90%) of reaction products at the entrance of the reactors, together with the fresh feed.

In cooperation with the catalyst manufacturer Clariant, Foster Wheeler has developed a new technology for SNG production: the VESTA process. In this process, the methanation reaction section previously described is preceded by the water shift reaction (clean shift):

\[
CO + H_2O = CO_2 + H_2
\]

The VESTA process does not need control of the gas composition entering the plant, and adapts itself according to inlet composition. Therefore the process can accept variations in the feedstock composition while maintaining the output specification.

In the conventional SNG processes, the risk of runaway of the methanation reaction is extremely high. In the VESTA process, however, such risk is avoided due to the presence of the CO₂ acting as a temperature damper. This implies that the CO₂ removal in the VESTA process is performed downstream of the methanation reactors rather than before, as in conventional processes (see Figure 6).
This choice permits:
- avoiding the installation of a recycle gas compressor to mitigate the temperature increase due to methanation (with subsequent higher investment and operating costs)
- use of a simple CO₂ removal system (amine, hot carbonates, etc.) because at that point the gas does not contain any “contaminant”
- easy production of high purity CO₂ without sulfur and other contamination

The VESTA process is extremely flexible and regardless of the selected gasification technology can produce up to 250,000 Nm³/h of SNG in a single train without recycle compressor and without risk of temperature runaway or metal dusting. The highest temperature in the VESTA process does not overcome 550°C, thus internal lining or high alloy steel reactors are not required.

**Biomass to SNG case study**

Foster Wheeler has made a technical and economic assessment of a large-scale biomass-to SNG plant in western Europe, using woody biomass as the main feedstock for the gasifier and producing approximately 200 MW\(_{th}\) (or 21,000 Nm³/h) of SNG.

The plant configuration chosen for this assessment is based on the use of the following main technologies, which are all ready for commercial application at large scale:
- Foster Wheeler Circulating Fluidized Bed (FW-CFB) gasifier, pressurized and oxygen-blown type;
- Catalytic reforming for tar removal from the syngas;
- Physical solvent washing for H₂S removal;
- Foster Wheeler/Clariant VESTA SNG technology;
- Chemical solvent washing for CO₂ removal.

The main technical and economical results are reported in Table 3.

**Conclusion**

The considerations made in this paper lead to the conclusion that SNG production via biomass gasification is technically feasible: the main technologies are available and sufficiently mature for commercial application, even at large scale.

Foster Wheeler has recently completed a technical and economic assessment of a large-scale biomass-to SNG plant, using woody materials as the main feedstock for the gasifier and producing approximately 200 MW\(_{th}\) (or 21,000 Nm³/h) of SNG.

The study demonstrated that, depending on the key economic assumptions, a biomass-to-SNG plant can be economically attractive, even without considering financial support from local governments that, in any case, is likely to be received for these types of plant, thus further improving the profitability of the investment.

Foster Wheeler continues to develop solutions in this field, including its technology leadership for the biomass gasification process through its proprietary CFB-based gasification technology and, at the same time as owner, together with Clariant, of a patented and novel SNG production process, VESTA.

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**Table 3: Technical/Economical Data of a Biomass-to-SNG plant**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Unit</th>
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<tr>
<td>Feedstock type</td>
<td>Woody material</td>
<td></td>
</tr>
<tr>
<td>Feedstock flowrate</td>
<td>130</td>
<td>t/h as received</td>
</tr>
<tr>
<td>Inlet thermal power</td>
<td>315-330</td>
<td>MW(_{th})</td>
</tr>
<tr>
<td>Outlet SNG flowrate</td>
<td>21,000</td>
<td>Nm³/h</td>
</tr>
<tr>
<td>Outlet thermal power (SNG)</td>
<td>200</td>
<td>MW(_{th})</td>
</tr>
<tr>
<td>Biomass to SNG efficiency</td>
<td>60-63</td>
<td>% (LHV)</td>
</tr>
<tr>
<td>Total investment cost (TIC)</td>
<td>340-370</td>
<td>Million €</td>
</tr>
<tr>
<td>Specific Total Investment Cost</td>
<td>1,700-1,990</td>
<td>€/kWth of SNG</td>
</tr>
</tbody>
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