Benchmarking Biomass Gasification Technologies for Fuels, Chemicals and Hydrogen Production

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DISCLAIMER

EXECUTIVE SUMMARY

As part of a previous study conducted at the National Energy Technology Laboratory (NETL), computer models were developed of the BCL (Battelle Columbus Laboratory) biomass gasifier. It became apparent during this analysis that the BCL gasifier may not be the best match of biomass gasification technology to downstream conversion technology for either liquid fuels, chemicals or hydrogen production. The BCL gasifier has only been demonstrated at relatively low operating temperatures and near-ambient pressures, conditions not typical of synthesis applications. Whether this gasifier can be operated successfully at other conditions is a question that must be addressed experimentally and is outside the scope of this analysis. It seems prudent, however, to consider other biomass gasification technologies, ones that might better match the intended syngas end use and are nearer to commercialization. The overall objective of this project was to survey and benchmark existing commercial or near-commercial biomass gasification technologies relative to end-use syngas applications. Data needed for modeling, simulation and analysis were the primary focus of this study.

A literature search on biomass gasification technology was completed to determine the current status of biomass gasification commercialization, identify near-commercial processes and collect reliable gasification data. More than 40 sources, including a number of web sites, provided data. The aim was not to select a 'superior' technology, but rather to collect, organize, verify and analyze biomass gasification data. Such data can be used in future studies to determine the best match of an available biomass gasification technology to a process application of interest. Fact sheets were developed for each technology, when sufficient data were available. Data are organized into the following six categories: biomass feedstock analyses, gasification operating conditions, syngas composition, emissions, capital cost, and supporting equipment. This information provides a reasonable basis for determining which biomass gasifiers seem most appropriate for any given application. It also provides insight into areas that might require further research.

This study considered the specific fuel and chemical applications: Fischer-Tropsch fuels, methanol, hydrogen, and fuel gas. Highly desirable syngas characteristics for these were identified, which were then used to evaluate technologies for a given end-use application. By far, directly heated bubbling fluidized bed (BFB) biomass gasification has been the most widely demonstrated of the technologies considered. It has been operated over a wide range of conditions including temperature, pressure and throughput.

Ideally, for fuels, chemicals and hydrogen applications, it is beneficial to operate at high temperatures. At temperatures greater than 1200-1300°C, little or no methane, higher hydrocarbons or tar is formed, and H_2 and CO production is maximized without requiring a further conversion step. The Tampella BFB gasifier has been operated at temperatures approaching this range (950°C). BFB gasifiers have been operated at the high pressures that would likely be used in fuels and chemical synthesis (>20 bar) and have also been operated with co-feeds of air, oxygen and steam. Varying the amounts of these co-feeds can be used to adjust the H_2/CO ratio of the syngas to match synthesis requirements.

Sufficient information currently exists to conduct conceptual design studies on these systems. *For all of these reasons, it therefore appears that for fuels, chemicals and hydrogen applications, BFB gasifiers currently have a clear advantage.*

Directly heated circulating fluidized bed (CFB) gasification of biomass has not been demonstrated to the same extent as BFB gasification. Very few demonstrations have been carried out at elevated pressures, and all results reported are for temperatures less than $1000^{o}C$. Demonstrations have not been conducted using pure oxygen as the oxidant. Fixed bed biomass gasifiers have also only been demonstrated at a limited range of conditions. Because of their tendency to produce large quantities of either tar or unconverted char, they have not been prime candidates for further development. Indirectly heated biomass gasification systems, both CFB and BFB are at an earlier stage of development, and their flexibility for a variety of applications has not been explored. They are inherently more complicated than directly-heated systems, due to the requirement for a separate combustion chamber, but they can produce a syngas with a very high heating value, ideal for CHP applications. *These systems, CFB (direct and indirect) and BFB (indirect), require further development in order to be considered suitable for fuels, chemicals and hydrogen.*

It is clear that further development work is necessary to establish operating limits for most biomass gasification technologies. The majority of past biomass gasifier demonstrations have been for the generation of process heat, steam and electricity. R&D outlined below, geared to producing syngas for fuels, chemicals and hydrogen production, would be beneficial for filling the data gaps identified in this report:

- Demonstration of CFB (direct and indirect) and BFB (indirect) gasifiers at pressures greater than 20 bar with various ratios of O_2 and steam as co-feeds

- Demonstration of all biomass gasification systems, both BFB and CFB, at temperatures greater than $1200^{o}C$

- Demonstration of all biomass gasification systems on a wider range of potential feedstocks

- Demonstration of biomass/coal co-gasification in commercial coal gasification systems

As evidenced by the many blanks appearing in the tables in this report, much of the data researchers have generated in past demonstrations has not been reported. Past conceptual design studies, primarily focussed on advanced technologies, have tended to adjust the operations of all steps following biomass gasification to match what little is known about the gasifier, and have avoided drastically altering gasifier operations due to the lack of data. Both these practices need to change.

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ACRONYMS

BCL	Battelle Columbus Laboratory
BFB	Bubbling Fluidized Bed
BIGCC	Biomass Integrated Gasification Combined Cycle
Btu	British Thermal Unit
CFB	Circulating Fluidized Bed
CHP	Combined Heat and Power
EPA	Environmental Protection Association
EPI	Energy Products of Idaho
FB	Fixed Bed
FT	Fischer-Tropsch
FERCO	Future Energy Resources Corporation
GTI	Gas Technology Institute
GW	Gigawatt
HRSG	Heat Recovery Steam Generator
MSW	Municipal Solid Waste
MTCI	Manufacturing and Technology Conversion International
NETL	National Energy Technology Laboratory
NREL	National Renewable Energy Laboratory
PRIMES	Producer Rice Mill Energy System
PSA	Pressure Swing Absorption
RDF	Refuse Derived Fuel
SEI	Southern Electric International
WGS	Water Gas Shift

1. BACKGROUND

As part of a previous study conducted at the National Energy Technology Laboratory (NETL), computer models were developed of the BCL (Battelle Columbus Laboratory) biomass gasifier. The models were used to develop conceptual designs for biomass-to-liquids and biomass-to-hydrogen plants, to size and cost these plants, and to calculate the required selling price of liquid fuels and hydrogen produced from biomass. Economics and greenhouse gas emissions were to be compared with more traditional approaches for converting biomass to fuel, such as the production of bioethanol or biodiesel, and to coal and petroleum coke-based gasification systems.

While the results obtained from the plant simulations based on the BCL gasifier were consistent with analyses reported earlier by the National Renewable Energy Laboratory (NREL) [1], a number of critical issues were identified which made the validity of any comparisons based on these simulations questionable. At the time of the study, BCL biomass gasification technology was unproven at commercial scale and was at a much earlier stage of development than either bioethanol or biodiesel production, both of which are commercial, or coal and coke gasification, which have been commercialized by Shell, Texaco, Destec and others. The BCL gasifier has since been successfully demonstrated at the McNiel Generating Station in Burlington, Vermont [2] by Future Energy Resources Corporation (FERCO), and new information should be available in the near future. However, uncertainty is likely to remain for many key performance parameters, and the BCL/FERCO technology may not be the best match of biomass gasification technology to downstream syngas conversion technology for either hydrogen or liquid fuels production. It therefore seems prudent to consider other biomass gasification technologies; ones that might better match the intended syngas end use and may be nearer to commercialization. There also exists considerable interest in hybrid systems, which are fed both biomass and coal or coke and produce power in addition to fuels, chemicals or hydrogen. These should also be included in any comparative analysis.

The overall objective of this project is to survey and benchmark existing-commercial or near-commercial biomass gasification technologies for suitability to generate syngas compatible with commercial or near-commercial end-use technologies for fuels, chemicals and hydrogen manufacture. The data compiled here can be used to answer the questions: "Where are we today?" "Where do we go now?" and "How do we get there from here?" Others have concentrated on the first question but generally have not collected or reported the data needed to answer the other two questions. The data needed for modeling, simulation and analysis is the primary focus of this study.

2. METHODOLOGY

A literature search on biomass gasification technology was done to determine the current status of biomass gasification commercialization, identify near-commercial processes and collect reliable gasification data. More than 40 sources, including a number of web sites, provided data on biomass gasification technologies. The goal was not to select a 'superior' technology, but rather to collect, organize, verify and assess biomass gasification process data. Such data can be used in future studies to determine the best match of an available biomass gasification technology to a process application of interest, such as chemical synthesis, fuel production, or combined heat and power (CHP) generation.

The scope has been limited to biomass gasification technologies that are at or near commercial availability and have been demonstrated in a large-scale operation. Though, several companies have discontinued work on biomass gasification, their efforts have provided valuable information on both demonstration and commercial size plants. However, one-time pilot or bench-scale gasification results are not included in this report, and biomass gasification technologies for which little or no process data are available are noted, but omitted from the tables.   Table 1 is a complete listing of the biomass gasification technologies considered in this study.

Table 1. Biomass Gasification Technologies Reviewed

1. Battelle Columbus Laboratory/FERCO (BCL/FERCO)
2. Gas Technology Institute (GTI)
3. Manufacturing and Technology Conversion International (MTCI)
4. Lurgi Energy
5. Sydkraft (In conjunction with Foster Wheeler)
6. Southern Electric International (SEI)
7. TPS Termiska Processor AB (Studsvik Energiteknik)
8. Stein Industry
9. Sofresid/Caliqua
10. Aerimpianti
11. Ahlstrom
12. Energy Products of Idaho (EPI, formerly JWP Energy Products)
13. Tampella Power, Inc.
14. Arizona State University*
15. University of Sherbrooke*
16. Voest Alpine (Univ. of Graz)*
17. Volund (Elkraft)
18. Iowa State University
19. Swiss Combi*
20. Carbona Inc. (Formerly Enviropower owned by Tampella)*
21. Producer Rice Mill Energy Systems (PRIMES)*
22. Sur-Lite*
23. Vattenfall Lime Kiln Gasifier*
24. Wellman Process Engineering
25. Union Carbide (PUROX)
26. Foster Wheeler

*Omitted due to size of experimental unit or lack of data

Fact sheets were developed for each technology where sufficient data were available (Appendix A). The gasification data were organized into the following six categories:

1. Biomass Feedstock Analyses
2. Gasification Operating Conditions
3. Syngas Composition
4. Emissions
5. Capital Cost
6. Supporting Equipment

This information provides a reasonable basis for determining which biomass gasifiers seem most appropriate for any given application. It also provides insight into areas that might require further research. For comparison, typical data for Shell coal gasification is also included throughout this survey.

3. GASIFIER CLASSIFICATION

Biomass gasification is the conversion of an organically derived, carbonaceous feedstock by partial oxidation into a gaseous product, synthesis gas or "syngas," consisting primarily of hydrogen (H_2) and carbon monoxide (CO), with lesser amounts of carbon dioxide (CO_2), water (H_2O), methane (CH_4), higher hydrocarbons (C_2+), and nitrogen (N_2). The reactions are carried out at elevated temperatures, 500-1400°C, and atmospheric or elevated pressures up to 33 bar (480 psia). The oxidant used can be air, pure oxygen, steam or a mixture of these gases. Air-based gasifiers typically produce a product gas containing a relatively high concentration of nitrogen with a low heating value between 4 and 6 MJ/m^3 (107-161 Btu/ft^3). Oxygen and steam-based gasifiers produce a product gas containing a relatively high concentration of hydrogen and CO with a heating value between 10 and 20 MJ/m^3 (268-537 Btu/ft^3).

3.1 Gasification Reactions

The chemistry of biomass gasification is complex. Biomass gasification proceeds primarily via a two-step process, pyrolysis followed by gasification (see Figure 1). Pyrolysis is the decomposition of the biomass feedstock by heat. This step, also known as devolatilization, is endothermic and produces 75 to 90% volatile materials in the form of gaseous and liquid hydrocarbons. The remaining nonvolatile material, containing a high carbon content, is referred to as char [4].
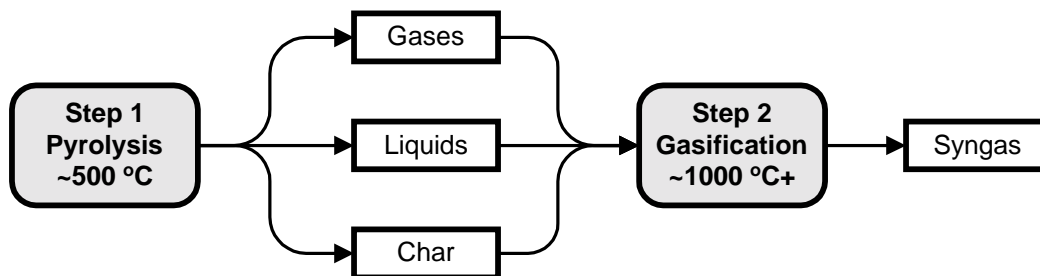
Figure 1. Gasification Steps

The volatile hydrocarbons and char are subsequently converted to syngas in the second step, gasification. A few of the major reactions involved in this step are listed below [3,4]:

Exothermic Reactions:

(1) Combustion	{*biomass volatiles/char*} $+ O_2 \rightarrow$	CO_2
(2) Partial Oxidation	{*biomass volatiles/char*} $+ O_2 \rightarrow$	CO
(3) Methanation	{*biomass volatiles/char*} $+ H_2 \rightarrow$	CH_4
(4) Water-Gas Shift	$CO + H_2O \rightarrow$	$CO_2 + H_2$
(5) CO Methanation	$CO + 3H_2 \rightarrow$	$CH_4 + H_2O$

Endothermic Reactions:

(6) Steam-Carbon reaction $\{biomass\ volatiles/char\} + H_2O \rightarrow CO + H_2$

(7) Boudouard reaction $\{biomass\ volatiles/char\} + CO_2 \rightarrow 2CO$
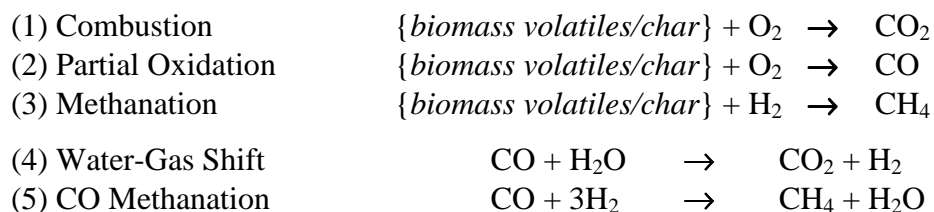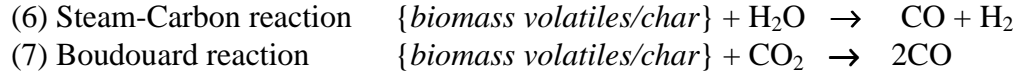
Heat can be supplied directly or indirectly to satisfy the requirements of the endothermic reactions.

Directly heated gasification conducts the pyrolysis and gasification reactions in a single vessel. An oxidant, air or oxygen, combusts a portion of the biomass (Reactions 1 & 2) to provide the heat required for the endothermic reactions. Pyrolysis requires between 5 and 15% of the heat of combustion of the feed to raise the reaction temperature and vaporize the products [4]. In these systems, the reactor temperature is controlled by the oxidant feed rate. If air is used as the oxidant, the product gas has a low heating value of 4 to 5 MJ/m^3 (107-134 Btu/ft^3) due to nitrogen dilution. Examples of this technology are the Gas Technology Institute (GTI) and the SynGas gasifiers.

An example of *indirectly heated gasification* technology is the BCL/FERCO gasifier. It utilizes a bed of hot particles (sand), which is fluidized using steam. Solids (sand and char) are separated from the syngas via a cyclone and then transported to a second fluidized bed reactor. The second bed is air blown and acts as a char combustor, generating a flue gas exhaust stream and a stream of hot particles. The hot (sand) particles are separated from the flue gas and recirculated to the gasifier to provide the heat required for pyrolysis. This approach separates the combustion Reaction 1 from the remaining gasification reactions, producing a product gas that is practically nitrogen free and has a heating value of 15 MJ/m^3 (403 Btu/ft^3) [5]. Reaction 2 is suppressed with almost all oxygen for the syngas originating in the feedstock or from steam (Reaction 6).

3.2 Biomass Feedstocks

Biomass is the organic material from recently living things, including plant matter from trees, grasses, and agricultural crops. The chemical composition of biomass varies among species, but basically consists of high, but variable moisture content, a fibrous structure consisting of lignin, carbohydrates or sugars, and ash [6]. Biomass is very non-homogeneous in its natural state and possesses a heating value lower than that of coal. The non-homogeneous character of most biomass resources (e.g., cornhusks, switchgrass, straw) pose difficulties in maintaining constant feed rates to gasification units. The high oxygen and moisture content results in a low heating value for the product syngas, typically <2.5 MJ/m^3 (67 Btu/ft^3). This poses problems for downstream combustors that are typically designed for a consistent medium-to-high heating value fuel.

Table 2 compares the proximate and ultimate analyses of several potential biomass gasifier feedstocks. Wood is the most commonly used biomass fuel. The most economic sources of wood for fuel are usually wood residues from manufacturers, discarded wood products diverted from landfills, and non-hazardous wood debris from construction and demolition activities. Fast-growing energy crops (e.g., short rotation hardwoods) show promise for the future, since they have the potential to be genetically tailored to grow

fast, resist drought and be easily harvested. It has been estimated that biomass feedstock costs range from \$16 to \$70 per dry ton [1,7].

Table 2. Potential Biomass Gasifier Feedstocks

	Ultimate Analysis (wt% dry basis)						Proximate Analysis (wt% dry basis)			
	C	H	N	O	S	Ash	Moisture	Volatiles	Fixed Carbon	Heating Value HHV (MJ/kg)
Agricultural Residues										
Sawdust	50	6.3	0.8	43	0.03	0.03	7.8	74	25.5	19.3
Bagasse	48	6.0	-	42	-	4	1	80	15	17
Corn Cob	49	5.4	0.4	44.6	-	1	5.8	76.5	15	17
Short Rotation Woody Crops										
Beech Wood	50.4	7.2	0.3	41	0	1.0	19	85	14	18.4
Herbaceous Energy Crops										
Switchgrass	43	5.6	0.5	46	0.1	4.5	8.4	73	13.5	15.4
Straw	43.5	4.2	0.6	40.3	0.2	10.1	7.6	68.8	13.5	17
Miscanthus	49	4.6	0.4	46	0.1	1.9	7.9	79	11.5	12
Municipal Solid Waste										
Dry Sewage	20.5	3.2	2.3	17.5	0.6	56	4.7	41.6	2.3	8
Coals										
Subbituminous	67.8	4.7	0.9	17.2	0.6	8.7	31.0	43.6	47.7	24.6
Bituminous	61.5	4.2	1.2	6.0	5.1	21.9	8.7	36.1	42.0	27.0

Compositions are approximate and may not sum exactly to 100.0%.
Biomass moisture contents reported are for dried feedstocks.
References [3,4,8]

3.3   Gasifier Types

A variety of biomass gasifier types have been developed. They can be grouped into four major classifications: fixed-bed updraft, fixed-bed downdraft, bubbling fluidized-bed and circulating fluidized bed. Differentiation is based on the means of supporting the biomass in the reactor vessel, the direction of flow of both the biomass and oxidant, and the way heat is supplied to the reactor. Table 3 lists the most commonly used configurations. These types are reviewed separately below.

Table 3. Gasifier Classification

Gasifier Type	Flow Direction		Support	Heat Source
	Fuel	Oxidant		
Updraft Fixed Bed	Down	Up	Grate	Combustion of Char
Downdraft Fixed Bed	Down	Down	Grate	Partial Combustion of Volatiles
Bubbling Fluidized Bed	Up	Up	None	Partial Combustion of Volatiles and Char
Circulating Fluidized Bed	Up	Up	None	Partial Combustion of Volatiles and Char

References [3,4,9]

3.3.1 Updraft Gasification

Also known as counterflow gasification, the updraft configuration is the oldest and simplest form of gasifier; it is still used for coal gasification. Biomass is introduced at the top of the reactor, and a grate at the bottom of the reactor supports the reacting bed. Air or oxygen and/or steam are introduced below the grate and diffuse up through the bed of biomass and char. Complete combustion of char takes place at the bottom of the bed, liberating CO_2 and H_2O. These hot gases (~1000°C) pass through the bed above, where they are reduced to H_2 and CO and cooled to 750°C. Continuing up the reactor, the reducing gases (H_2 and CO) pyrolyse the descending dry biomass and finally dry the incoming wet biomass, leaving the reactor at a low temperature (~500°C) [2,3,4]. Examples are the PUROX and the Sofresid/Caliqua technologies.

The advantages of updraft gasification are:

- Simple, low cost process

- Able to handle biomass with a high moisture and high inorganic content (e.g., municipal solid waste)

- Proven technology

The primary disadvantage of updraft gasification is:

- Syngas contains 10-20% tar by weight, requiring extensive syngas cleanup before engine, turbine or synthesis applications

3.3.2 Downdraft Gasification

Also known as cocurrent-flow gasification, the downdraft gasifier has the same mechanical configuration as the updraft gasifier except that the oxidant and product gases flow down the reactor, in the same direction as the biomass. A major difference is that this process can combust up to 99.9% of the tars formed. Low moisture biomass (<20%) and air or oxygen are ignited in the reaction zone at the top of the reactor. The flame generates pyrolysis gas/vapor, which burns intensely leaving 5 to 15% char and hot combustion gas. These gases flow downward and react with the char at 800 to 1200°C, generating more CO and H_2 while being cooled to below 800°C. Finally, unconverted char and ash pass through the bottom of the grate and are sent to disposal [3,4,9].

The advantages of downdraft gasification are:

- Up to 99.9% of the tar formed is consumed, requiring minimal or no tar cleanup

- Minerals remain with the char/ash, reducing the need for a cyclone

- Proven, simple and low cost process

The disadvantages of downdraft gasification are:

- Requires feed drying to a low moisture content (<20%)
- Syngas exiting the reactor is at high temperature, requiring a secondary heat recovery system
- 4-7% of the carbon remains unconverted

3.3.3 Bubbling Fluidized Bed

Most biomass gasifiers under development employ one of two types of fluidized bed configurations: bubbling fluidized bed and circulating fluidized bed. A bubbling fluidized bed consists of fine, inert particles of sand or alumina, which have been selected for size, density, and thermal characteristics. As gas (oxygen, air or steam) is forced through the inert particles, a point is reached when the frictional force between the particles and the gas counterbalances the weight of the solids. At this gas velocity (minimum fluidization), bubbling and channeling of gas through the media occurs, such that the particles remain in the reactor and appear to be in a "boiling state" [10]. The fluidized particles tend to break up the biomass fed to the bed and ensure good heat transfer throughout the reactor.

The advantages of bubbling fluidized-bed gasification are [4,9]:

- Yields a uniform product gas
- Exhibits a nearly uniform temperature distribution throughout the reactor
- Able to accept a wide range of fuel particle sizes, including fines
- Provides high rates of heat transfer between inert material, fuel and gas
- High conversion possible with low tar and unconverted carbon

The disadvantages of bubbling fluidized-bed gasification are:

- Large bubble size may result in gas bypass through the bed

3.3.4 Circulating Fluidized Bed

Circulating fluidized bed gasifiers operate at gas velocities higher than the minimum fluidization point, resulting in entrainment of the particles in the gas stream. The entrained particles in the gas exit the top of the reactor, are separated in a cyclone and returned to the reactor.

The advantages of circulating fluidized-bed gasification are [4,9]:

- Suitable for rapid reactions
- High heat transport rates possible due to high heat capacity of bed material
- High conversion rates possible with low tar and unconverted carbon

The disadvantages of circulating fluidized-bed gasification are [4,9]:

- Temperature gradients occur in direction of solid flow

- Size of fuel particles determine minimum transport velocity; high velocities may result in equipment erosion

- Heat exchange less efficient than bubbling fluidized-bed

Most of the gasifier technologies described in this report employ a bubbling fluidized-bed or circulating fluidized-bed system.

3.4   Supporting Processes

3.4.1 Feedstock Preparation
Biomass feedstock preparation can be broken down into two steps: feed size selection/reduction and feed drying. Feed preparation capital cost, which is in the range of $11,100 to $17,400/TPD, is dependent on many factors, including biomass characteristics and gasifier requirements [11]. Costs increase for difficult to handle feeds (e.g., straw) and high moisture feeds (e.g., >30%) that require extensive drying prior to gasification.

Several methods are available to provide a continuous feedstock supply to the gasifier. There is a consensus, however, that some difficulties continue to exist in maintaining a reliable biomass handling, storage, and feeding system, whether to an atmospheric or pressurized gasifier. This results from inconsistent moisture, density, size and thermal energy content of most biomass feeds. For example, mechanical handling of straw is difficult due to its low bulk density (<200 kg/m^3). It must be either handled in bales or must be chopped or pelletized to enable mechanical or pneumatic handling [9]. Some types of wood are soft, moist and stringy and tend to interfere with certain mechanical feeding methods, such as screw feeders. Biomass is resized and reshaped using various methods, including rotating knives, rollers, hammer milling, chopping, shredding, pulverizing and pelletizing. Biomass is transported from storage silos or lock hoppers to the gasifier via a conveyor or a pneumatic system.

The majority of the gasification technologies reviewed require feedstock moisture to be below a specified level. This level varies from less than 10% for Lurgi to less than 70% for Foster Wheeler [4]. Rotary, steam and cyclonic drying methods use heat supplied by either a boiler, combustion turbine, or engine exhaust gases (EPI) or are fueled directly by product gas (Lurgi). Gasification of high moisture content biomass is possible but at the expense of a higher system energy requirement and a dirtier syngas [4]. High moisture content fuels generally decrease reactor-operating temperature and, therefore, may increase methane content and lower hydrogen content.

3.4.2 Syngas Conditioning
The synthesis gas produced by biomass gasification can contain one or more of the contaminants listed in Table 4. The identity and amount of these contaminants depend on the gasification process and the type of biomass feedstock.

Tars are mostly polynuclear hydrocarbons (such as pyrene and anthracene) that can clog engine valves, cause deposition on turbine blades or fouling of a turbine system leading to decreased performance and increased maintenance.   In addition, these heavy

hydrocarbons interfere with synthesis of fuels and chemicals. Conventional scrubbing systems are generally the technology of choice for tar removal from the product syngas. However, scrubbing cools the gas and produces an unwanted waste stream. Removal of the tars by catalytically cracking the larger hydrocarbons reduces or eliminates this waste stream, eliminates the cooling inefficiency of scrubbing, and enhances the product gas quality and quantity.

Table 4. Syngas Contaminants

Contaminant	Example	Potential Problem
Particles	Ash, char, fluid bed material	Erosion
Alkali Metals	Sodium and Potassium Compounds	Hot corrosion, catalyst poisoning
Nitrogen Compounds	NH_3 and HCN	Emissions
Tars	Refractive aromatics	Clogging of filters
Sulfur, Chlorine	H_2S and HCl	Corrosion, emissions, catalyst poisoning

Reference [12]

An example of a tar cracking technology is one developed by Battelle using a disposable cracking catalyst in conjunction with steam addition [13]. Cracking is carried out by the following reaction [11]:

$$C_nH_{2m} + nH_2O \rightarrow nCO + (m+n)H_2$$
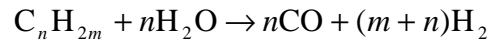
The Battelle catalyst also has water-gas shift activity. This increases the hydrogen content of the product gas so that it is suitable for fuel cell and other applications.

Incompletely converted biomass and ash particulate removal is accomplished with cyclones, wet scrubbing, or high-temperature filters. A cyclone can provide primary particulate control, but is not adequate to meet gas turbine specifications. A high-temperature ceramic filter system, such as one under development by Westinghouse, can be used to remove particulates to acceptable levels for gas turbine applications [14,15]. Since this filter can withstand temperatures in the 800°C range, the thermal losses associated with gas cooling and cleaning can be reduced.

Water scrubbing can remove up to 50% of the tar in the product gas, and when followed by a venturi scrubber, the potential to remove the remaining tars increases to 97% [2]. The wastewater from scrubbing can be cleaned using a combination of a settling chamber, sand filter and charcoal filter. This method is claimed to clean the wastewater discharge to within EPA drinking water standards but at the expense of increased capital cost [2].

3.5 Co-Gasification

Co-gasification of coal and biomass is a relatively new area of research. Preliminary results from several pilot studies have shown promising results in terms of quality of the syngas and reduced environmental impact. Although coal is the world's most plentiful fossil fuel and is extensively used in power generation, it has had a serious impact on the environment as evidenced by acid rain caused by SOx, and NOx emissions [16]. Emissions of the greenhouse gas CO_2 during coal combustion have also become a major global concern. Biomass has a lower energy content than coal; however, its use for energy production can significantly contribute to the reduction of net CO_2 emissions. These two fuels, when co-gasified, exhibit synergy with respect to overall emissions, including greenhouse gas emissions, without sacrificing the energy content of the product gas.

Biomass, whether as a dedicated crop or a waste-derived material, is renewable. However, the availability of a continuous biomass supply can be problematic. For example, crop supply may be decreased by poor weather or by alternative uses, and the availability of a waste material can fluctuate depending on variations in people's behavior. With co-gasification, adjusting the amount of coal fed to the gasifier can alleviate biomass feedstock fluctuations. This approach may also allow biomass feedstocks to benefit from the same economies of scale as achieved with coal gasification that may be necessary for the economic production of fuels, chemicals and hydrogen.

There are a number of options for integrating coal and biomass within a co-gasification process. These are shown in Figure 2:

1) Co-feeding biomass and coal to the gasifier as a mixture

2) Co-feeding biomass and coal to the gasifier using separate gasifier feed systems

3) Pyrolizing the biomass followed by co-feeding pyrolysis char and coal to the gasifier

4) Gasifying the biomass and coal in separate gasifiers followed by a combined fuel gas clean-up [17].

Each approach has benefits and drawbacks and ultimately the best choice will depend on the results of further research and analysis.
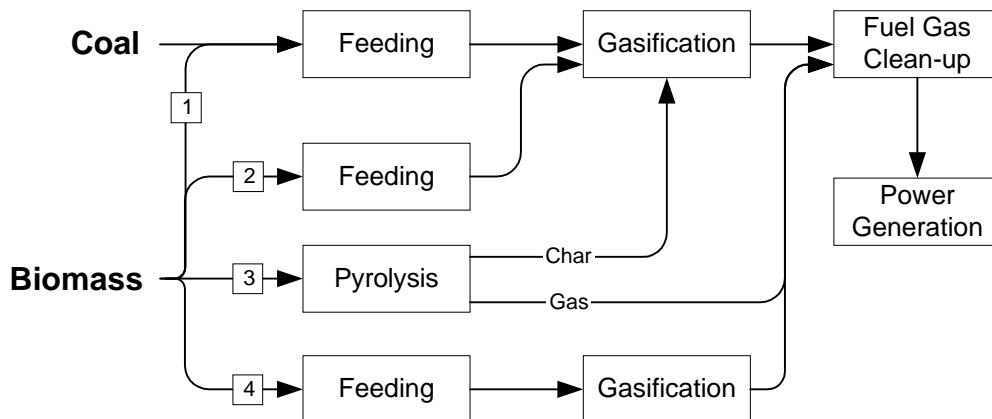

Figure 2. Coal/Biomass Co-Gasification Integration Options

4. SYNGAS APPLICATIONS

The composition of biomass-gasification derived syngas will vary based on many factors, including reactor type, feedstock and processing conditions (temperature, pressure, etc.). Figure 3 depicts syngas end-use options discussed in this study. This study considered the specific fuel and chemical applications: Fischer-Tropsch fuels, methanol and hydrogen.

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┌─────────────────────────────────────────────────────────┐
│ Syngas                                                    │
│ Generation        ┌──────────────────┐                    │
│                   │   Gasification   │                    │
│                   └──────────────────┘                    │
│                            │                              │
├─────────────────────────────────────────────────────────┤
│ Syngas                     ▼                              │
│ Intermediate  ( Syngas -- H₂, CO, CO₂, CH₄, N₂, H₂O, C₂+ )│
│                     │                    │                │
├─────────────────────────────────────────────────────────┤
│ Syngas              ▼                    ▼                │
│ Conversion    ┌───────────┐      ┌──────────────┐         │
│               │ Synthesis │      │  Combustion  │         │
│               └───────────┘      └──────────────┘         │
│                     │                    │                │
├─────────────────────────────────────────────────────────┤
│ End-Use             ▼                    ▼                │
│ Product       Fuels or Chemicals    Power or Heat         │
└─────────────────────────────────────────────────────────┘
```
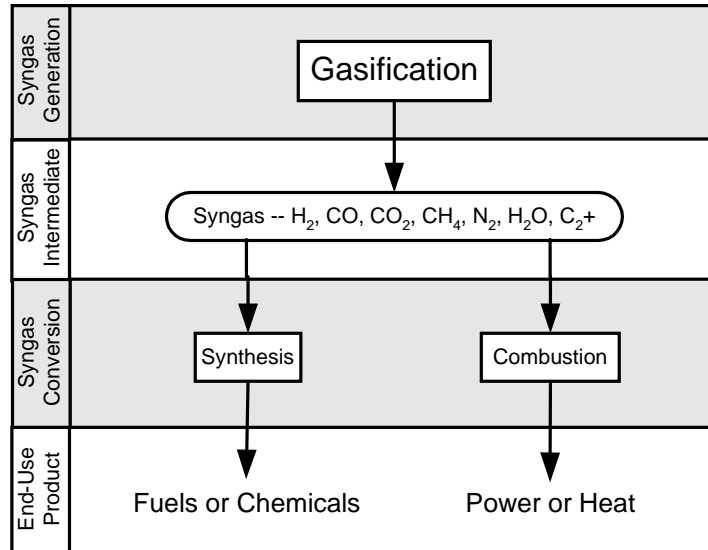
Figure 3. Syngas Conversion Options

Table 5 summarizes desirable syngas characteristics for the various options shown in Figure 3. In general, syngas characteristics and conditioning are more critical for fuels and chemical synthesis applications than for hydrogen and fuel gas applications. High purity syngas (i.e. low quantities of inerts such as N_2) is extremely beneficial for fuels and chemicals synthesis since it substantially reduces the size and cost of downstream equipment. However, the guidelines provided in Table 5 should not be interpreted as stringent requirements. Supporting process equipment (e.g., scrubbers, compressors, coolers, etc.) can be used to adjust the condition of the product syngas to match those optimal for the desired end-use, albeit, at added complexity and cost. Specific applications are discussed in more detail below, in order of increasing syngas quality requirements.

Table 5. Desirable Syngas Characteristics for Different Applications

Product	Synthetic Fuels	Methanol	Hydrogen	Fuel Gas	
	FT Gasoline & Diesel			Boiler	Turbine
H_2/CO	0.6 [a]	~2.0	High	Unimportant	Unimportant
CO_2	Low	Low [c]	Not Important [b]	Not Critical	Not Critical
Hydrocarbons	Low [d]	Low [d]	Low [d]	High	High
N_2	Low	Low	Low	Note [e]	Note [e]
H_2O	Low	Low	High [f]	Low	Note [g]
Contaminants	<1 ppm Sulfur Low Particulates	<1 ppm Sulfur Low Particulates	<1 ppm Sulfur Low Particulates	Note [k]	Low Part. Low Metals
Heating Value	Unimportant [h]	Unimportant [h]	Unimportant [h]	High [i]	High [i]
Pressure, bar	~20-30	~50 (liquid phase) ~140 (vapor phase)	~28	Low	~400
Temperature, °C	200-300 [j] 300-400	100-200	100-200	250	500-600

(a) Depends on catalyst type. For iron catalyst, value shown is satisfactory; for cobalt catalyst, Near 2.0 should be used.
(b) Water gas shift will have to be used to convert CO to H_2; CO_2 in syngas can be removed at same time as CO_2 generated by the water gas shift reaction.
(c) Some CO_2 can be tolerated if the H_2/CO ratio is above 2.0 (as can occur with steam reforming of natural gas); if excess H_2 is available, the CO_2 will be converted to methanol.
(d) Methane and heavier hydrocarbons need to be recycled for conversion to syngas and represent system inefficiency.
(e) N_2 lowers the heating value, but level is unimportant as long as syngas can be burned with a stable flame.
(f) Water is required for the water gas shift reaction.
(g) Can tolerate relatively high water levels; steam sometimes added to moderate combustion temperature to control NOx.
(h) As long as H_2/CO and impurities levels are met, heating value is not critical.
(i) Efficiency improves as heating value increases.
(j) Depends on catalyst type; iron catalysts typically operate at higher temperatures than cobalt catalysts
(k) Small amounts of contaminants can be tolerated

4.1 Fuel Gas Applications

Approximately 13% of the world energy demand is met with biomass fuels. Biomass represents 4% of the primary energy used in the United States, whereas biomass utilization is 17% in Finland and 21% in Sweden [20]. The U.S. possesses about 10 GW of installed capacity from biomass, which is the single largest source of non-hydro renewable energy. This installed capacity consists of approximately 7 GW derived from forest and agricultural industry residues, 2.5 GW from municipal solid waste, and 0.5 GW from other sources, such as landfill gas-based production.

Biomass can produce electric power via a direct-combustion boiler/steam turbine. The overall biomass-to-electricity efficiency is limited by the theoretical limit to the efficiency of power generation in a steam turbine, the inherently high moisture of biomass feedstocks, and because of the smaller plant sizes typical of biomass systems. The efficiency of a biomass/steam turbine system is between 20 and 25%. Power generation can also be accomplished via gasification of biomass, followed by a

combustion engine, combustion turbine, steam turbine or fuel cell. These systems can produce both heat and power (CHP - Combined Heat and Power) and can achieve greater system efficiencies in the range of 30 to 40% [5]. The power generation scheme employed establishes syngas specifications. There is more latitude with regard to syngas composition for engine combustion than for turbine combustion. Gas turbines have emerged as the best means for transforming heat to mechanical energy and are now key components of the most efficient electrical generating systems.

To be considered interchangeable with conventional fossil fuels (natural gas or distillate oils) and to ensure maximum flexibility for industrial or utility applications, syngas heating value needs to be above 11 MJ/m^3 (300 Btu/ft^3) [2]. The heating value for natural gas is approximately 37 MJ/m^3 (1020 Btu/ft^3). As indicated in Table 5, a high hydrocarbon content (CH_4, C_2H_6,…) corresponds to a higher heating value for the syngas.

Biomass integrated gasification combined cycle (BIGCC) technology has been considered for electricity production in the sugarcane and pulp and paper industries, and for general agricultural waste and waste wood conversion. A typical BIGCC application involves combustion of the syngas in a combustion turbine to generate electricity in a topping cycle. The hot exhaust gas is directed through a heat recovery steam generator (HRSG) producing steam that is sent to a steam turbine to generate additional electricity in a bottoming cycle, or used for process heating. The first plant to demonstrate the BIGCC technology was built in 1993 at Varnamo, Sweden, and produced 6 MW of power and 9 MW of heat. The system was comprised of a pressurized circulating fluidized bed gasifier, a gas turbine, and a steam turbine. The overall efficiency (CHP) of the Varnamo plant is ~83%, and the electrical efficiency is 33% [21].

4.2   Hydrogen

Hydrogen is currently produced in large quantities via steam reforming of hydrocarbons over a Ni catalyst at ~800^{o}C (1472^{o}F) [19]. This process produces a syngas that must be further processed to produce high-purity hydrogen. The syngas conditioning required for steam reforming is similar to that which would be required for a biomass gasification-derived syngas; however, tars and particulates are not as much of a concern. To raise the hydrogen content, the product syngas is fed to one or more water gas shift (WGS) reactors, which convert CO to H_2 via the reaction:

$$CO + H_2O \rightarrow H_2 + CO_2$$
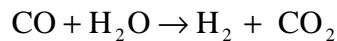
The gas stream leaving the first WGS stage has a CO content of about 2%; in a second stage this is reduced further to about 5000 ppm. The remaining CO can be removed by a pressure-swing adsorption (PSA) system.

4.3   Methanol

Commercial methanol synthesis involves reacting CO, H_2, and steam over a copper-zinc oxide catalyst in the presence of a small amount of CO_2 at a temperature of about 260^{o}C (500^{o}F) and a pressure of about 70 bar (1015 psi) [8]. The methanol synthesis reaction is equilibrium controlled, and excess reactants (CO and H_2) must be recycled to obtain

economic yields. The formation of methanol from synthesis gas proceeds via the water-gas-shift reaction and the hydrogenation of carbon dioxide:

$$\begin{array}{llll} CO + H_2O & = & H_2 + CO_2 & \text{Water-gas-shift} \\ \underline{3H_2 + CO_2} & = & \underline{CH_3OH + H_2O} & \text{Hydrogenation of carbon dioxide} \\ 2H_2 + CO & = & CH_3OH & \end{array}$$
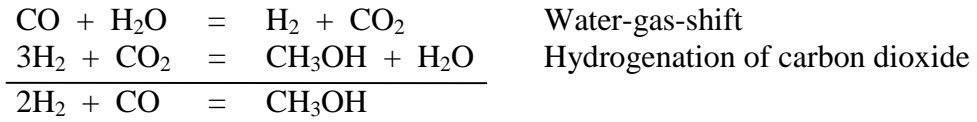
Methanol production also occurs via direct hydrogenation of CO, but at a much slower rate [18].

$$\begin{array}{llll} 2H_2 + CO & = & CH_3OH & \text{Hydrogenation of carbon monoxide} \end{array}$$

To best use the raw product syngas in methanol synthesis and limit the extent of further syngas treatment and steam reforming, it is essential to maintain:

- A H_2/CO of at least 2

- A CO_2/CO ratio of about 0.6 to prevent catalyst deactivation and keep the catalyst in an active reduced state

- Low concentrations of N_2, CH_4, C_2+, etc. to prevent the build up of inerts within the methanol synthesis loop

- Low concentrations of CH_4 and C_2+ to limit the need for further steam reforming.

4.4 Synthetic FT Fuels

Synthetic fuels such as gasoline and diesel can be produced from synthesis gas via the Fischer-Tropsch (FT) process. There are several commercial FT plants in South Africa producing gasoline and diesel, both from coal and natural gas, and a single plant in Malaysia feeding natural gas. The FT synthesis involves the catalytic reaction of H_2 and CO to form hydrocarbon chains of various lengths (CH_4, C_2H_6, C_3H_8, etc.). The FT synthesis reaction can be written in the general form:

$$(n/2 + m)H_2 + mCO \rightarrow C_mH_n + mH_2O$$

where m is the average chain length of the hydrocarbons formed, and n equals $2m+2$ when only paraffins are formed, and $2m$ when only olefins are formed. Iron catalyst has water-gas-shift (WGS) activity, which permits use of low H_2/CO ratio syngas.

Gasifier product gases with a H_2/CO ratio around 0.5 to 0.7 is recommended as a feed to the FT process when using iron catalyst. The WGS reaction adjusts the ratio to match requirements for the hydrocarbon synthesis and produce CO_2 as the major by-product. On the other hand, cobalt catalysts do not have WGS activity, and the H_2 to CO ratio required is then $(2m + 2)/m$. Water is the primary by-product of FT synthesis over a cobalt catalyst.

As shown in Table 5, the composition of syngas intended for fuel gas applications is different from that required for synthetic fuel or chemical synthesis. A high H_2, low CO_2, low CH_4 content is required for chemical and fuel production. In contrast, a high H_2

content is not required for power production, as long as a high enough heating value is supplied through CH_4 and C_2+ hydrocarbons.

5. SURVEY RESULTS

5.1 Operating Conditions

Table 6 lists gasification operating conditions for fifteen technologies for which sufficient data were available. Of the technologies listed, seven are bubbling fluidized bed (BFB) gasifiers, six are circulating fluidized bed (CFB) gasifiers and two are fixed-bed (FB) updraft gasifiers. The majority of the processes listed have been tested with a variety of biomass feedstocks. However, results have only been reported for a few different feedstocks, and it is believed that many of the feedstocks reported have only been tested in small-scale bench units. The primary feedstocks, for which product syngas composition data were available are identified in Table 6. These were typically wood, pulp sludge, MSW, RDF and corn stover. The feed rate ranged from 136 to 7,575 kg/hr (300-16,665 lb/hr); pressure from 1 to 33 bar (14.7-480 psi); and average reactor temperature from 725 to $1400^{o}C$ (1337-2550^{o}F).

Table 7 summarizes the ranges of conditions tested for the various biomass gasifier classifications: BFB (directly heated), CFB (directly heated), fixed bed, indirectly-heated CFB (BCL/FERCO), and indirectly heated BFB (MTCI). For comparison, Table 7 also includes typical operating conditions for the commercial Shell entrained-flow gasifier. The Shell coal gasification process has been demonstrated at a throughput that is an order of magnitude greater than normally encountered with biomass. The availability of large quantities of coal at centralized locations enables coal gasification facilities to take advantage of economies of scale.

Operating biomass gasifiers at or above atmospheric pressure has both benefits and drawbacks depending upon the intended application for the syngas. Pressurized gasifiers are complex, costly and have a higher capital cost, both for the gasifier and associated feed system. On the other hand, the gas supplied to a combustion turbine or conversion process is at pressure, avoiding the need for costly gas compression. Exit temperatures vary considerably reflecting gas clean up and heat recovery systems. Some investigators have only reported temperatures downstream of this equipment.

Sources of oxygen used in biomass gasification are air, pure oxygen and steam, or some combination of these. Air is the most widely used oxidant, avoiding the requirement for oxygen production, and was used in over 70% of the gasifiers that have been tested. However, the use of air results in a low heating value gas, 4 to 6 MJ/m^3 (107-161 Btu/ft^3), only suitable for boiler and engine operation. The use of oxygen produces a medium heating value gas, 10 to 15 MJ/m^3 (268-403 Btu/ft^3), suitable for combustion turbine applications or for conversion to gasoline or methanol [9]. The BCL/FERCO and MTCI gasifiers produce the highest heating value syngas with 16.7 to 18 MJ/m^3 (448-483 Btu/ft^3). Oxygen is supplied by steam in these indirectly heated systems.

Table 6. Individual Gasifier Operating Conditions

	EPI	Stein	Tampella	ISU	GTI	SEI	Purox	Sofresid
Type	BFB	BFB	BFB	BFB	BFB	BFB	FB	FB
Primary Feedstock	Wood	Wood	Wood	Corn	Wood	Wood	MSW	MSW
Throughput (tonne/day)	100	60	45	4.5	12	181	181	195
Pressure (bar)	1	15	20-23	1	35	1	1	1
Temperature (^{o}C)	650	700-750	850-950	730	816	650-815	-	1300-1400
Reactant 1	Air	O_2	Air	Air	O_2	Air	O_2	Air
Input (kg/kg feed)	2.0	0.6	0.4	-	0.27	1.45	-	-
Reactant 2	-	Steam	Steam	-	Steam	-	-	-
Input (kg/kg feed)	-	0.4	0.5	-	0.64	-	-	-
Gas Output (m^3/h)	8793	2900	-	-	335	4845	-	33,960
Exit Temperature (^{o}C)	621	-	300-350	-	816	800	-	-
Heating Value (MJ/m^3)	5.6	5.52	4 – 6	4.5	13	5.7	-	7.92

	TPS	Aerimp-ianti	Foster Wheeler	Lurgi	Sydkraft	BCL/ FERCO[a]	MTCI[b]	
Type	CFB	CFB	CFB	CFB	CFB	CFB	BFB	
Primary Feedstock	Wood	RDF	Wood	Bark	Wood	Wood	Pulp	
Throughput (tonne/day)	9	45-100	14.5	84-108	-	24	7	
Pressure (bar)	1	1	1	1	18	1	1	
Temperature (^{o}C)	700-950	850-900	900	800	950-1000	600-1000	790-815	
Reactant 1	Air	Air	Air	Air	Air	Air	-	
Input (kg/kg feed)	-	1.7	1.7	1.25	-	0.08	-	
Reactant 2	-	-	-	-	-	Steam	Steam	
Input (kg/kg feed)	-	-	-	-	-	0.31	2.2	
Gas Output (m^3/h)	-	3500-14000	1181	9700-12500	-	800	-	
Exit Temperature (^{o}C)	-	800-900	700	600	-	820	-	
Heating Value (MJ/m^3)	4-7	4.5-5.5	7.5	5.8	5	18	16.7	

[a] Indirectly Heated CFB with separate combustor
[b] Indirectly-Heated BFB with separate combustor
[c] Fluid Bed - Entrained Flow (no circulation)
References [1,2,3,4,5,9,10,13]
“- “ indicates unknown or not reported

Table 7. Gasifier Operating Conditions Summary

	BFB Range	CFB Range	Fixed Bed Range	BCL/ FERCO[a]	MTCI[b]	Shell[c]
Feedstock	Various	Various	Various	Wood	Pulp	Coal
Throughput (tonne/day)	4.5-181	9-108	181-195	24	7	2155
Pressure (bar)	1-35	1-19	1	1	1	30
Temperature (^{o}C)	650-950	800-1000	1300-1400	600-1000	790-815	1400
Reactant 1	O_2 or Air	Air	O_2 or Air	Air	-	O_2
Input (kg/kg feed)	0.4-2.2	1.25-1.7		0.08	-	0.98
Reactant 2	Steam	-	-	Steam	Steam	Steam
Input (kg/kg feed)	0.5-0.64	-	-	0.31	2.2	~0
Gas Output (m^3/h)	335-8793	1181-12500	33,960	800	-	1.48×10^6
Exit Temperature (^{o}C)	300-800	600-900	-	820	-	240
Heating Value (MJ/m^3)	4-13	4-7.5	7.92	18	16.7	9.51

See footnotes with Table 6

5.2   Syngas Composition

Table 8 presents syngas compositions for a number of the biomass gasification technologies examined in this survey. These compositions were cited as being from existing commercial applications or based on large-scale process development units. A large number of parameters influence composition, including feedstock, pressure, temperature and oxidant. Quite a few biomass gasification studies failed to report the content of tar and other impurities in the syngas. At the operating temperatures reported (see Table 6), significant quantities of methane, higher hydrocarbons and tar can be expected. Due to the higher operating temperatures used in coal gasification, coal-derived syngas contains essentially no methane or other hydrocarbons and tar. However, since coal usually contains sulfur and nitrogen, significant quantities of H_2S and NH_3 are present in the raw syngas. Table 9 summarizes the results for various gasifier classifications.

Table 8. Compositions of Biomass-Derived Syngas

	EPI[a]	Stein	Tampella	ISU	GTI	SEI	Purox
Type	BFB	BFB	BFB	BFB	BFB	BFB	FB
Feedstock	Wood	Wood	Wood	Wood	Wood	Wood	MSW
H_2	5.8	19.9	11.3	4.1	14.8	12.7	23.4
CO	17.5	26.2	13.5	23.9	11.7	15.5	39.1
CO_2	15.8	40.3	12.9	12.8	22.39	15.9	24.4
H_2O	dry	dry	17.7	dry	dry	dry	dry
CH_4	4.65	-	4.8	3.1	10.8	5.72	5.47
C_2+	2.58	-	-	-	0.13	2.27	4.93
Tars	-	0.11	-	-	0.27	-	(in C_2+)
H_2S	-	-	-	-	0.01	-	0.05
O_2	-	-	-	0.2	-	-	-
NH_3	-	-	-	-	0.10	-	-
N_2	51.9	13.4	40.2	55.9	40.3	47.9	-
H_2/CO Ratio	0.3	0.8	0.8	0.2	1.6	0.8	0.6
Heating Value (MJ/m^3)	5.6	5.5	4-6	4.5	13.0	5.6	-
	TPS	Aerimp-ianti	Foster Wheeler	Lurgi	Sydkraft	BCL/ FERCO[a]	MTCI[b]
Type	CFB	CFB	CFB	CFB	CFB	CFB-other	BFB-other
Feedstock	RDF	RDF	Wood	Bark	Wood	Wood	Pulp
H_2	7 – 9	7-9	15-17	20.2	11	14.9	43.3
CO	9 – 13	9-13	21-22	19.6	16	46.5	9.22
CO_2	12 – 14	12-14	10-11	13.5	10.5	14.6	28.1
H_2O	10 – 14	10-14	dry	dry	12	dry	5.57
CH_4	6-9	6-9	5-6	(in C_2+)	(in C_2+)	17.8	4.73
C_2+	-	-	-	3.8	6.5	6.2	9.03
Tars	-	0.5-1	-	<1g/m^3	(in C_2+)	-	Scrubbed
H_2S	-	-	-	Very low	-	-	0.08
O_2	-	-	-	-	-	0	0
NH_3	-	-	-	-	-	0	0
N_2	47 - 52	47-52	46-47	42.9	44	0	0
H_2/CO Ratio	0.7	0.7	0.7	1.0	0.7	0.3	4.6
Heating Value (MJ/m^3)	4-7	4.5-5.5	7.5	5.8	5.0	18.0	16.7

References [1,2,3,4,5,9,10,13]
See footnotes with Table 6

Table 9. Syngas Compositions Summary

	BFB Range	CFB Range	BCL/ FERCO[a]	MTCI[b]	Fixed Bed Purox	Shell[c]
Feedstock	Various	Various	Wood	Pulp	MSW	Coal
H_2	5-26	7-20	14.9	43.3	23.4	24
CO	13-27	9-22	46.5	9.22	39.1	67
CO_2	12-40	11-16	14.6	28.1	24.4	4
H_2O	<18	10-14	dry	5.57	dry	3
CH_4	3-11	<9	17.8	4.73	5.47	0.02
C_2+	<3	<4	6.2	9.03	4.93	0
Tars	<0.11	<1	-	Scrubbed	-	0
H_2S	~0	~0	-	0.08	0.05	1
O_2	<0.2	0	0	0	-	0
NH_3	0	0	0	0	-	0.04
N_2	13-56	46-52	0	0	-	1
H_2/CO Ratio	0.2-1.6	0.6-1.0	0.3	4.6	0.6	0.36
Heating Value (MJ/m^3)	4-13	4-7.5	18.0	16.7	-	9.51

See footnotes with Table 6

5.3   Emissions

Only limited data on biomass gasifier emissions were available. These are presented in Table 10. Emissions are highly variable and depend on gasifier type, feedstock, process conditions (temperature and pressure) and gas conditioning systems. For example, indirect gasification systems generate flue gas emissions from the combustion of additional fuel, char, a portion of the biomass feed, or in the case of MTCI, natural gas [9]. Gasification of municipal solid waste and sewage sludge results in ash containing heavy metals. A major concern with these feedstocks is the potential for heavy metals to leach into the environment following ash disposal.   Though emissions from coal gasification are not given below, they are in general higher than those generated from biomass gasification, due to the inherently low sulfur and ash content of most biomass.

Table 10. Biomass Gasification Emissions

Technology	MTCI	GTI	Lurgi	Aerimpianti
Input				
Reactor Type	BFB	BFB	CFB	CFB
Feedstock	Pulp sludge	Wood	Bark	RDF
Emissions				
Liquid Waste (tar/oil) (kg/kg feed)	-	0.03	Low	-
Solid Waste (char/ash) (kg/kg feed)	0.091	0.03	0.01 – 0.04	250-630 kg/h
Product Tar Content	-	2 – 3 %	1 g/m^3	25-40 kg/h
CO	-	-	250 mg/m^3	-
NOx	25 ppm	-	250 mg/m^3	-
SO$_2$	9 ppm	-	100 mg/m^3	<300 ppm
Organic Carbon	-	-	150 mg/m^3	-
NH$_3$	-	-	5 mg/m^3	-
H$_2$S	-	-	5 mg/m^3	-
Technology	**SEI**	**TPS**	**Sofresid**	
Input				
Reactor Type	BFB	CFB	FB	
Feedstock	Wood	Wood	MSW	
Liquid Waste (tar/oil) (kg/kg feed)	592	<100	0	
Solid Waste (char/ash) (kg/kg feed)	-	-	10	
Product Tar Content	Burned	100 g/m^3	Burned	
CO	-	-	-	
NOx	-	-	120 ppm	
SO$_2$	-	-	79 ppm	
Organic Carbon	-	-	<10 ppm	
NH$_3$	-	-	-	
H$_2$S	-	-	-	

References [1,2,3,4,5,9,10,13]

5.4 Capital Costs

Very few of the investigations cited in this report provided capital cost information on their technology, and what was provided typically lacked detail. Thus, the literature cost information was supplemented with estimates by the authors based on the process description and what ever other data could be found. For example, in some cases the investigator did not specify whether costs included supporting processes, such as feed pretreatment, feed handling and storage, or product gas treatment. Supporting processes can increase total gasification costs by 70 to 80% [4]. Furthermore, several reported gasification plant capital costs were for the total power plant, which included the gas turbine, HRSG, and steam turbine. Costs of these supporting facilities were estimated and subtracted from the reported cost to obtain an estimate of the cost of the stand-alone gasifier. This approach, while crude, enabled a cost range and average to be determined for directly heated BFB, and the indirectly heated BCL/FERCO and MTCI gasification technologies. These values are reported in Table 11. Based on the information available, no estimate could be made for directly heated CFB gasifiers. These units, owing to their simpler design are expected to be less costly than BFB gasifiers. Capital costs have been escalated to 2001 dollars and are presented on both a $/tPD (dry basis) of feedstock gasified and $/GJ/h of syngas produced basis.

The range of capital cost reported for directly heated BFB gasifiers is large and overlaps with the reported capital costs for the Shell coal gasifier on a tPD basis. However, the average capital cost for a BFB biomass gasifier is $25,000 per tPD. This is less than Shell at $37,300 per tPD and can be attributed to the higher reactivity of biomass versus coal and the less severe conditions (i.e., lower temperature) required for biomass gasification. On an energy basis, however, the capital cost of producing coal-derived syngas is much cheaper ($1,400 vs. $29,500 per GJ/h), a result of the much higher energy content of coal relative to biomass (240-270 vs. 10-20 MJ/kg). The indirectly heated gasifiers appear to be competitive with the average cost for a directly heated BFB gasifier. They are likely to be somewhat more expensive than directly heated gasifiers due to the added complexity of the process, though this is not very apparent from the estimates given in Table 11.

Table 11. Gasification Capital Costs

Technology Type	Type	Size (tonne/day)	Capital Cost ($ 10^6)	Capital Cost ($ 10^3/tPD)	Capital Cost ($/GJ/h Syngas)
BFB Range [9,13]	BFB	170-960	2-36	13-45	21,600-54,900
BFB Average [9,13]	BFB	615	16.1	25.0	29,500
BCL/FERCO[a] [9,11,22]	CFB	740-910	18-26	24.5-28.4	33,000-48,000
MTCI[b] [9]	BFB	44	1.1	25.2	-
Shell Coal Gasifier[c]	-	2,200	80.5	37.3	1,400

See footnotes with Table 6

Little if any information related to operating costs could be identified in the literature, and these costs (maintenance, labor, etc.) have not been considered in this survey.

5.5   Supporting Equipment

It is important to consider the equipment needed to produce syngas meeting the requirements of a particular application. Increasing process complexity is indicative of increased labor and maintenance costs and decreased plant availability. Any additional process equipment needed upstream or downstream of the gasifier were identified along with end-use application, and are reported in Table 12. The identification of complete equipment lists and the costing of this supplemental equipment for each technology were beyond the scope of this project.

A majority of gasifier technologies require drying the feed to a specified moisture content prior to gasification. This step requires energy and, therefore, decreases overall efficiency. Pelletization is the process by which biomass is transformed into a compact, dense, easy-to-handle feed feed, but this is not practiced or required for most biomass gasifiers. Separation is primarily used in handling RDF to segregate the heavier waste from lighter "fluff." Size reduction and pressurization were specified in several feed handling systems. Not included in Table 12 is equipment, such as storage silos, conveyors, feed screws, lock hoppers, weighing systems, etc., that is required for almost if not all of the gasification technologies considered.

An additional combustion chamber is used to supply the heat needed by indirectly heated gasifiers. An oxygen plant is required for processes employing pure oxygen or oxygen enriched air as a reactant. Oxygen has been used as a reactant in very few biomass applications to date. This has been an advantage for CHP applications, since an oxygen plant increases capital costs substantially and is not required for this application. Some gasifiers require additional ash removal and handling systems. A secondary partial oxidation reactor is used as a tar cracker to remove any tars present in syngas. Other supplementary equipment includes syngas filtering, electrostatic precipitator, emissions control and scrubber systems. In almost all cases, some type of syngas clean up is required.

Table 12. Gasification Supporting Equipment

Technology	Feed	Upstream	Gasification	Downstream	End Use
1. MTCI	Pulp sludge	No treatment	a, cc	sc	Non-specific
2. GTI	Wood	d, z, c	o		Fuel gas
3. BCL/FERCO	Wood	No treatment	a, cc	sc, po, e, f	Synthesis gas
4. Lurgi	Bark	d, z	a	sc	Fuel kilns
5. Sydkraft & Foster Wheeler	Wood	d, c		f, sc, po	Turbine
6. SEI	Wood chips	d, z	a	No cleaning	Fuel kilns
7. TPS	Wood residue	d	a	sc, po	Engine, turbine, or boiler
8. Stein	Wood chips	d, c	o	sc, po	Synthesis gas
9. Sofresid	MSW		a	e	Boiler (power)
10. Aerimpianti	RDF	p, d, z		f	Boiler (power)
11. EPI	Wood chips	d, z		No cleaning	Boiler (power)
12. Tampella	Wood/Coal	c, d, z	a	f, po	Turbine
13. PUROX	MSW	No treatment	a, o	f	Non-specific

(a) - ash removal   (c) - pressurization   (d) - drying   (e) - electrostatic precipitator
(f) - syngas filtering   (o) - oxygen plant   (p) - pelletization   (s) - separation
(z) – sizing   (cc) - combustion chamber   (ec) - emissions control
(po) - secondary partial oxidation reactor   (sc) - scrubber
References [4,9]

6. CONCLUSIONS & RECOMMENDATIONS

6.1 Potential Applications

The data presented in Tables 6 through 12 were compared with the syngas characteristics described in Table 5 for various end-use applications. Multiple factors, including syngas composition, processing conditions (pressure, temperature, etc), emissions (PM, tar), capital costs and supporting equipment (process complexity), were considered. Based on this comparison, the following conclusions can be drawn as to the suitability of the various classes of biomass gasifiers for different syngas applications.

6.1.1 BFB Gasifiers

By far, directly heated bubbling fluidized bed biomass gasification has been the most widely demonstrated of the technologies considered. It has been operated over a wide range of conditions, such as temperature, pressure and throughput, using a variety of biomass feedstocks. For fuels, chemicals and hydrogen applications, it is beneficial to operate at high temperatures as is done for coal gasification. At temperatures greater than 1200-1300^{o}C, little or no methane, higher hydrocarbons or tar is formed, and H_2 and CO production is maximized without requiring a further conversion step. The Tampella BFB gasifier has been operated with biomass at temperatures (950^{o}C max) approaching but still well short of this range. Several BFB gasifiers have been operated at the high pressures that would be used in fuels and chemical synthesis (>20 bar). It is advantageous in these applications to operate the gasifier at a pressure higher than that of the synthesis reactor to avoid the requirement for costly gas compression between these two steps. However, this expense is somewhat balanced by the need for more complicated solid feedstock handling equipment upstream of the gasifier. Particle size reduction may be necessary with most BFB gasifiers, and the biomass would likely need to be dried to increase operating temperatures.

BFB gasifiers have been operated with co-feeds of air, oxygen and steam. Nitrogen dilution of the syngas is especially detrimental for synthesis application and an oxygen plant is normally required. Varying the relative amounts of oxygen and steam can be used as a means to adjust the H_2/CO ratio of the syngas to match synthesis requirements. For hydrogen production, it is desirable to maximize the production of H_2 over CO in the gasifier by promoting the water-gas-shift reaction. If an all fuels or chemicals product slate is desired, steam reforming or partial oxidation of the methane and higher hydrocarbons present in the syngas is required. The H_2/CO ratio requirement for methanol synthesis makes the requirement of an external shift reactor or separation step a strong likelihood; however, for FT synthesis an iron catalyst can be employed to adjust this ratio within the FT reactor. If it results in higher H_2/CO ratios, the high CO_2 production from BFB gasifiers is not undesirable. Other than tar cracking, which would be necessitated if higher operating temperatures cannot be achieved, gas cleanup will be minimal for synthesis applications. BFB gasifiers are possibly the lowest capital cost option among the advanced biomass gasification technologies. Sufficient information exists to conduct conceptual design studies on these systems. *It, therefore, appears that for fuels, chemicals and hydrogen applications, existing BFB gasifiers currently have an advantage.*

6.1.2 CFB Gasifiers

Directly heated circulating fluidized bed gasification of biomass has not been demonstrated to the same extent as BFB gasification. Very few tests have been carried out at elevated pressures; and, as with BFB gasifiers, all results reported are for temperatures less than 1000^{o}C. Elevated pressure operations have been tested, but not to pressures as high as with BFB gasifiers (19 vs. 35 bar max). Feed particle size reduction will likely be necessary for CFB gasifiers, and the biomass would likely need to be dried to increase operating temperatures. *Demonstrations have not been conducted using pure oxygen or steam as reactants. This is possibly the most severe restriction limiting their current consideration for synthesis applications.* The reported CO_2 contents of syngas from CFB gasifiers are low, as are the H_2/CO ratios. This results from the suppression of the water gas shift reaction, which can be promoted through steam addition. No capital costs could be estimated for CFB gasifiers due to a lack of sufficient data in the literature.

6.1.3 Fixed Bed Gasifiers

Fixed bed biomass gasifiers have also only been demonstrated over a limited range of conditions. *Because of their tendency to produce large quantities of either tar or unconverted char, they have not been prime candidates for further development.* Their chief advantage is their ability to handle extremely inhomogeneous feedstocks such as MSW, and they should not be ruled out for waste-to-fuels applications.

6.1.4 Indirectly Heated Gasifiers

The indirectly heated biomass gasification systems, both CFB (BCL/FERCO) and BFB (MTCI), are at an early stage of development, and their flexibility for a variety of applications has not been explored. These units have only been tested at atmospheric pressure. They are inherently more complicated than directly-heated systems due to the requirement for a separate combustion chamber, but can produce a syngas with a very high heating value, ideal for CHP applications. This is also reflected in their higher unit capital costs. But, they do not require oxygen or air as a reactant for gasification, an advantage in all applications, since an oxygen plant is not required (thus, a capital cost and efficiency penalty is not incurred for this unit), and nitrogen dilution does not occur. However, their high yields of methane and higher hydrocarbons poses a greater challenge for fuels, chemicals and hydrogen production. If an all fuels or chemicals product slate is desired, steam reforming or partial oxidation is required. This requirement can be somewhat tempered by operating at high steam addition rates to promote the water gas shift reaction within the gasifier. Conceptual design studies have been conducted with these systems; however, with the current data, they require the addition of a steam reforming step to convert methane and other hydrocarbons to syngas and syngas compression to synthesis pressures. *These systems, CFB (direct and indirect) and BFB (indirect) require further development in order to be fairly evaluated for fuels, chemicals and hydrogen applications.*

6.1.5 Co-Gasification & Co-Production

As was pointed out earlier, biomass can be co-gasified with coal. A combined system offers significant operating and environmental advantages for both coal and biomass. Higher pressures, temperatures and throughputs can be achieved with existing

commercial coal gasification technologies. This approach may also allow biomass feedstocks to benefit from the same economies of scale as achieved with coal gasification. This may be necessary in order to produce fuels, chemicals and hydrogen at competitive costs. Major uncertainties, however, exist in how to integrate the two feedstocks and processes.

In a similar tone, the co-production of power with fuels, chemicals or hydrogen may improve the performance of biomass gasification systems. Low purity, high methane content syngas would be less of a problem for such a scenario. Methane and unconverted syngas leaving the conversion reactor can be combusted in a gas turbine to produce power to meet on-site demand and for sale across the plant fence. Similar hybrid systems co-producing fuels and power have been proposed based on coal gasification. As with co-gasification, the best approach to process integration remains an open issue.

6.2   Data Needs Assessment

Based on the above discussion, it is clear that further development work is necessary to establish operating limits for most biomass gasification technologies. The majority of past biomass gasifier demonstrations have been for the generation of process heat, steam and electricity, and current development activities are focused on producing electricity more efficiently by integrating the gasification system with a gas turbine. The following R&D, geared to producing syngas for fuels, chemicals and hydrogen production, would be beneficial for filling the data gaps identified in this report:

- Demonstration of CFB (direct and indirect) and BFB (indirect) gasifiers at pressures greater than 20 bar with various ratios of O_2 and steam as co-feeds

- Demonstration of all biomass gasification systems, both BFB and CFB, at temperatures greater than $1200^{\circ}C$

- Demonstration of all biomass gasification systems on a wider range of potential feedstocks

- Demonstration of biomass/coal co-gasification in commercial coal gasification systems

As evidenced by the many blanks appearing in the tables in this report, much of the data researchers have generated in past demonstrations has not been reported. Past conceptual design studies, primarily focussed on advanced technologies, have tended to adjust the operations of all steps following biomass gasification to match what little is known about the gasifier and have avoided drastically altering gasifier operations due to the lack of data. Both these practices need to change. Sufficient, although limited, information is only currently available on BFB gasifiers to examine the economics of converting biomass to fuels, chemicals and hydrogen. Conceptual designs have not, but should be, developed for this technology for these applications. These cases could then serve as a baseline for comparing other, more-advanced but less-developed, indirect BFB and direct and indirect CFB gasification technologies and for hybrid co-gasification/co-production scenarios, as data becomes available from further research on these systems.

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Appendix A: Biomass Gasification Fact Sheets

Developer:	Wellman Process Engineering
Information Source:	[Reed page 3-87]

1. Background/History: Wellman Process Engineering, located in Oldbury, England has been constructing boilers, coal and wood gasifiers and other thermal equipment for over 75 years.

2. Technology Description: The Wellman process consists of a typical updraft gasifer capable of handling up to 10 ton/day of wood. A cleanup system consisting of a thermal oxidation reactor, catalytic cracker and a gas scrubbing system has been the focus of research over the past 10 years. The goal is to clean and prepare the product gas (tar and particulate removal), then to test it with several engines.

3. Future Plans: Continue to quantify the amount of tar removal required for long term engine use.

4. Existing Process Data:

Process type: Fixed Bed Updraft Gasification

Process size (pilot, commercial….) Process Development Unit

Feedstock: Wood

Product: LHV gas

Yield (kg/kg feed): na

Use: Engine

Feedstock throughput (kg/h): 380 (10 ton/day)

Reactor conditions:

Pressure (atm): na

Temperature ($^{\circ}$C): 600 - 1000 (Ranges from pyrolysis to oxidation zone)

Reactant: Air/Steam

Rate (kg/kg feed): na

5. Product:

	Raw Gas	Thermally Cracked	Catalytically Cracked
Hydrogen	6.9	11.8	18
Carbon monoxide	29.5	16.5	8.9
Carbon dioxide	6.1	14.1	12.8
Methane		Included in C2+	
C2+	22.2	2.3	2.2
Oxygen			
Nitrogen	35.3	55.3	58.1
Total	**100**	**100**	**100**
Design gas output rate (Nm^3/h feed):	na		
Gas exit temperature ($^{\circ}$C):	100		
Heating value (MJ/m^3):	5.53	4.55	4.3

6. Utilties:

7. Costs:

Capital: na

Operating: na

Developer:	Volund (Ansaldo)
Information Source:	[Reed page 3-80]
1. Background/History:	The Volund gasifier was constructed in 1989 at a power plant located in Denmark. The gasifier is owned by Elkraft and operated by Volund and the Danish Technological Institute.
2. Technology Description:	Straw gasifier. Straw fed by screw feeder, pelletized to a bulk density of 200-400 kg/m^3 and fed at a maximum rate of 500 kg/h to a dixed bed updraft gasifier with a 2 meter outside diameter. An air/steam mixture is utilized as the oxidant and also utilized for temperature control. Product gas is fed to a burner. The system has a venturi scrubber to remove tars and particulates from the syngas.
3. Future Plans:	The pilot plant has been operating since 1993 and operated over 12,000 hours, producing more than 90% of all the heat for the city. Further research is focused on product gas cleanup (especially tars) to fuel an engine.
4. Existing Process Data:	
Process type:	Fixed Bed Updraft Gasification
Process size (pilot, commercial…)	Pilot plant
Feedstock:	Straw
Product:	LHV gas
Yield (kg/kg feed):	1.81-2.55
Use:	Currently flared at pilot plant
Feedstock throughput (kg/h):	500 (1.24 MWth or 13 ton/day)
Reactor conditions:	
Pressure (atm):	Atmospheric
Temperature ($^\circ$C):	na
Reactant:	Air/Steam mixture
Rate (kg/kg feed):	0.98 - 1.86
5. Product:	Dry (Straw fed at 300 kg/h)
Hydrogen	4.4
Carbon monoxide	11.6
Carbon dioxide	14.7
Methane	4
C2+	-
Oxygen	1
Nitrogen	64.3
Total	**100**
Design gas output rate (Nm^3/h feed):	1.40-1.97
Gas exit temperature ($^\circ$C):	250
Heating value (MJ/m^3):	2.6-5.0
6. Utilties:	
7. Costs:	
Capital:	na
Operating:	na

Developer:	Union Carbide (Purox Process)
Information Source:	[Reed page 3-47]
1. Background/History:	Development started in 1975 with cooperation from the EPA and DOE. Four plants constructed to treat MSW ranging from 10 ton/day to 200 ton/day.
2. Technology Description:	Purox process consists of a typical updraft fixed bed gasifier. Oxygen is fed at the bottom of the furnace (combustion zone) where it reacts with the char residue from the pyrolysis zone. The temperature is high enough in the combustion zone to melt and fuse all non-combustibles into a molten slag which is separated and cooled in a separate quench tank. The hot gases from the combustion zone rise through the descending waste, pyrolyzing the waste into a gaseous mixture of 38% CO and 23 % H2 on a dry basis. Exit temperature is between 180-300 C. A gas clean-up system removes particlates and condensibles, leaving a relatively clean gas which can be used for heat or chemical synthesis. [Reed]
3. Future Plans:	Gas currently being flared and the focus on future research is on gas cleanup involving tar and particulate removal.
4. Existing Process Data:	
Process type:	Fixed Bed Updraft Gasification
Process size (pilot, commercial….)	Commercial
Feedstock:	MSW
Product:	MHV gas
Yield (kg/kg daf):	na
Use:	Drying and parboiling rice and power generation.
Feedstock throughput (kg/hr):	7 tons/hr (200 ton/day)
Reactor conditions:	
Pressure (atm):	na
Temperature (^{o}C):	750 C - 1100 C
Reactant:	Oxygen
Rate (kg/kg feed):	0.2
5. Product:	
Hydrogen	23.43
Carbon monoxide	39.06
Carbon dioxide	24.41
Methane	5.47
C2+	4.93
Sulfur (as H$_2$S)	0.05
H$_2$O	
Other	2.65
Total	**100**
Design gas output rate (m^3/h):	na
Gas exit temperature (^{o}C):	180 - 300
Heating value (MJ/m^3):	13.7
6. Utilities:	na
7. Costs:	
Capital:	na
Operating:	na

Developer:	Gas Technology Institute (Gas Research Institute + Institute of Gas Technology)
Information Source:	[Bridgwater, Appendix II page 54]
1. Background/History:	The Institute of Gas Technology is a not for profit research, development and educational institute with approximately 15 years of biomass gasification technology.
2. Technology Description: PILOT PLANT	Goal is the gasification of biomass in a pilot scale 11 tonne/day, pressurized single-stage, oxygen blown, fluidized bed gasifier to produce medium heating value gas suitable as an industrial fuel gas, or for upgrading to substitute natural gas or synthesis gas. The gasifier can be operated either air or oxygen blown, at pressures to 32.7 bar (470 psi) and at temperatures between 850 C to 900 C.
	The RENUGAS gasifier is a single stage fluidized bed reactor with a deep bed of inert solids that provide stable fluidization behavior and needed heat capacity for efficient transfer of energy released by the combustion to the endothermic devolatilization and gasification reactions. The use of a deep single-stage bed of inert solids yields high carbon conversion and low oils and tars production.
3. Future Plans:	The Hawaiian plant is no longer functioning at this time.
4. Existing Process Data:	
Process type:	Bubbling Fluidized Bed Gasification
Process size (pilot, commercial):	Process Development Unit
Feedstock:	Woody biomass (bark and leaves)
Product:	MHV gas
Yield (kg/kg daf feed):	2.47
Use:	Fuel gas, syngas
Feedstock throughput (kg/h):	136 - 455 (3.6 - 12 ton/day)
Reactor conditions:	
Pressure (bar):	33
Temperature (^{o}C):	816
Reactant 1:	Oxygen
Rate (kg/kg feed):	0.27
Reactant 2:	Steam
Rate (kg/kg feed):	0.64
Gaseous waste flowrate (kg/dg daf):	n/a
Liquid waste flowrate (kg/kg feed):	0.03
Solid waste flowrate, ash (kg/kg daf):	0.03
5. Product:	Dry gas composition, volume %
Hydrogen	25.3
Carbon monoxide	16
Carbon dioxide	39.4
Methane	17.8
C2+	1.5
Oxygen	-
Nitrogen	0
Chlorine	0
Sulfur	-
H_2O	-
Other	-
Total	**100**
Design gas output rate (m^3/h feed):	335
Gas exit temperature (^{o}C):	816
Heating value (MJ/m^3):	12.97
Heavy metals content (define)(mg/m^3):	n/a
Particulate content (pilot test data) (g/m^3):	n/a
6. Utilities:	na
7. Costs:	
Capital:	na
Operating:	na

Developer:	Manufacturing and Technology Conversion International, Inc.(aka ThermoChem)	
Information Source:	[Bridgwater, Appendix II page 82]	

1. Background/History:

The technical feasibility of a 'pulse enhanced', indirectly heated, fluidized bed gasifier was confirmed in 1986. A 1/2 ton per hour demonstration scale unit was then constructed at a paper mill in Canada.

2. Technology Description:

7 ton/day demonstration unit.
Feed is stored in a small hopper and transported to the reactor bed via a screw mechanism. The gasifier vessel is 4 m high, bed height is 1.8 m and the freeboard is 1.22 m. The pressure at the base of the gasifier is 10 psig and the pressure at the gasifier exit is 1 psig. The normal operating bed temperature is 815 ^{o}C (1500 ^{o}F). Two bed materials were tested--sand and limestone. Bed is fluidized with superheated steam.

3. Future Plans:

As of dated report, it is planned to test a gas turbine fueled with the gas produced from the MTCI gasifier. MTCI has submitted a proposal to the US DOE for an integrated gas turbine gasifier system utilizing a paper mill sludge feedstock. Work was planned to build a 2.5-5 ton/h gasifier to be built in 1993-1994.

4. Existing Process Data:

Process type:	Bubbling Fluidized Bed Gasification
Process size (pilot, commercial…..)	7 ton/day demonstration unit
Feedstock:	Pulp mill sludge
Product:	MHV gas
Yield (kg/kg feed):	0.821
Use:	Combust to raise steam.
Feedstock throughput (kg/h):	181-272 (7 ton/day)

Reactor conditions:

Pressure (bar):	~1
Temperature (^{o}C):	788 - 815

Reactant:

	Steam
Rate (kg/kg feed):	1.73 - 2.60

5. Product:

	Test 1	Test 2
Dry Basis	Limestone Bed	Sand Bed
Hydrogen	45.86	35.06
Carbon monoxide	9.77	24.26
Carbon dioxide	29.73	20.79
Methane	5.01	10.42
C_2	6.12	8.62
C_3	1.96	0.5
C_4	1.48	0.3
H_2S	0.08	0.05
Oxygen	0	0
Nitrogen	0	0
Chlorine	0	0
Sulfur	0	0
H_2O	0	0
Total	**100.0**	**100**
Design gas output rate (m^3/h):	n/a	n/a
Gas exit temperature (^{o}C):	n/a	n/a
Heating value (MJ/m^3):	16.24	17.14
Heavy metals content (define)(mg/m^3):	n/a	n/a
Particulate content (pilot test data) (g/m^3):	n/a	n/a

6. Utilities:

Water (g/ton)	120
Electric Consumption (kW/ton)	20

7. Costs:

Capital:	$1.1MM	$22,900/TPD
Operating:		

Developer:	Battelle Columbus Laboratory
Information Source:	[Bridgwater, Appendix II page 30]
	[Reed page 3-3]

1. Background/History: Developed under the sponsorship from the US DOE at the Battelle Columbus Lab. 240 mm diameter plant process completed in 1980 and ran until 1986. RDF tests were conducted in 1988.

2. Technology Description:
PILOT PLANT

Gasifier is 10 inch diameter and 7 meters high. Steam blown, atmospheric pressure. Steam rate is held constant to insure fluidization. Sand, char & gas exit the reactor, pass through a cyclone, and solids (char) passed to a combustor.

The endothermic reactions are separated from the exothermic oxidation reactions resulting in the high heating value gas by using two separate reactors. Heat is transferred between the combustor and gasifier by circulating sand (indirect heating).

Process thermal efficiency was 72%. Gas yields of up to 0.95 kg/kg daf feed are possible and depends on the process conditions (temperature….)

3. Future Plans: Ready to construct a commercial plant in 1992. The minimum acceptable commercial plant size is approximately 200 tonne/day. At lower throughputs, the % heat loss is high and the maximum size is limited to feed accessibility.

4. Existing Process Data:

Process type:	Circulating Fluidized Bed Gasification
Process size (pilot, commercial…)	Pilot/Research Development Unit
Feedstock:	Wood (chips, shredded bark, sawdust, whole tree, chips, shredded stump material)
Product:	MHV fuel gas
Yield (% wt):	75
Use:	Fuel gas
Feedstock throughput (kg/h):	1000 (26 ton/day)

Reactor conditions:

Reactor pressure (bar):	1	
Reactor temperature (^{o}C):	600 - 1000	
Combustion reactor pressure (bar):	15	The second reactor is a 'combustion' reactor. The char accumulated on the
Combustion reactor temperature (^{o}C):	1300	sand is combusted providing the endothermic heat in the primary reactor.

Reactant 1:	Air
Rate (kg/kg feed):	0.08
Reactant 2:	Steam
Rate (kg/kg feed):	0.31

5. Product: Dry gas composition, volume %

Hydrogen	14.9
Carbon monoxide	46.5
Carbon dioxide	14.6
Methane	17.8
C2+	6.2
Oxygen	0
Nitrogen	0
Chlorine	0
Sulfur	0
H_2O	0.65
Other	0
Total	**100.65**
Design gas output rate (Nm^3/kg feed):	0.8
Gas exit temperature (^{o}C):	820
Heating value (MJ/Nm^3):	18

6. Utilities:

7. Costs:

Capital:	1000 ton/day would be $25.2 MM (2001 dollars)
Operating:	The cost of wood, bark and sawdust in Sept 1985 was estimated to be $25/daf ton.

Developer:	Studsvik Energiteknik AB (Now TPS-Thermal Process Studsvik)
Information Source:	[Bridgwater, Appendix II page 106]
	[Reed]-- page 3-69
1. Background/History:	TPS Termiska Processor AB (formerly part of Studsvik Energiteknik AB) is a privately owned R&D company based in Sweden. The company works in the field of energy and environmental process research and technology development.
2. Technology Description:	Gasification of woody biomass or minicipal waste in an atmospheric circulating
Commercial plant built but only pilot data is given.	gasifier for the production of a fuel gas for use in a duel fuel engine, a gas turbine or as a boiler/furnace/kiln fuel. A secondary circulating fluidized bed reactor cracks any tars in the product gas.
	Two 15MWth RDF fuelled FB gasifiers have been installed in Greve in Chianti by Aerimianti SpA.
3. Future Plans:	
4. Existing Process Data:	
Process type:	Circulating Fluidized Bed Gasification
Process size (I.e. pilot, commercial…):	Data is from pilot scale
Feedstock:	Wood
Product:	LHV gas
Yield (kg/kg wet feed):	n/a
Use:	Fuelling duel fuel engines, gas turbines, or gas burners

Feedstock throughput (kg/h):   500   13 Ton/day   *Pilot Unit   78 ton/day commercial scale--Italy

Reactor conditions:	
Reactor pressure (bar):	1
Reactor temperature (^{o}C):	700-900
Second reactor pressure (bar):	1 This reactor is used for tar cracking of the raw product gas.
Second reactor temperature (^{o}C):	850 - 950
Reactant:	Air
Rate (kg/kg dry feed):	na
5. Product:	Dry gas composition
Hydrogen	7-9
Carbon monoxide	9-13
Carbon dioxide	12-14
Methane	6-9
C2+	-
Oxygen	-
Nitrogen	47-52
Chlorine	n/a
Sulfur	n/a
H_2O	10-14
Other	0.5-1.0
Heating value (MJ/Nm^3):	4-7
6. Utilities:	
7. Costs:	
Capital:	$27.5MM $100000/TPD $155/MBtu/h
Operating:	

| Developer: | Lurgi Energy |
| Information Source: | [Bridgwater, Appendix II page 74] |

1. Background/History:

2. Technology Description:

Circulating fluidized bed bark gasification system (atmospheric operation) installed in 1986, for the production of a low heating value (LHV) gas from bark to fuel a lime kiln originally fueled by fuel oil. Operational as of April 1992.

Bark is dried before use from between 54-63 wt% to approximately 10 wt%. Bark is shredded to a maximum size of 30mm.

The low heating value gas is used to fuel a lime kiln fitted with a multifuel burner (heavy oil, LHV gas and off gas from the pulp production). The total LHV gas demand by the lime kiln is 800 Nm^3/h.

3. Future Plans:

As of 1992, investigate fueling a combustion engine with LHV gas. Solve problems with moisture fluctuation and large pieces of feed sticking in the feed system.

4. Existing Process Data:

Process type:	Circulating Fluidized Bed Gasification
Process size (pilot, commercial….)	Commercial
Feedstock:	Bark

Product:	LHV gas
Yield (kg/kg daf):	1.2-1.3
Use:	Lime kiln firing

Feedstock throughput (kg/hr):	3500 - 4500	(90 - 120 ton/day)

Reactor conditions:

Pressure (atm):	1
Temperature (^{o}C):	800

Reactant:	Air
Rate (kg/kg feed):	1.23-1.26

Liquid waste flowrate (from dryer scrubber):	low	
Solid waste flowrate, ash (kg/kg daf):	0.01-0.04	(1.5-3.3 wt % carbon)

5. Product:

	Bark (Dry)	RDF* (Wet)	* Pilot Plant Data
Hydrogen	20.2	8.27	
Carbon monoxide	19.6	9.76	
Carbon dioxide	13.5	9.3	
Methane	Included in C2+	1.55	
C2+	3.8	0.64	
Oxygen	0	0	
Nitrogen	42.9	43.06	
Sulfur (as H_2S)	very low	0.07	
H_2O	0	27.35	
Other	0		
Total	**100**	**100**	
Design gas output rate (m^3/h):	9700-12500		
Gas exit temperature (^{o}C):	600		
Heating value (MJ/m^3):	5.8	3.2	
Heavy metals content (define)(mg/m^3):	N/A	<1.1	
Particulate content (pilot test data) (g/m^3):	50	18	

6. Utilities:

7. Costs:

Capital:	$8.7MM	$72,700/TPD treated	$126.9/MBtu/h
Operating:	N/A		
Product or Production Costs:	Cost of LHV gas is $4.04/GJ. (compared with heavy oil at $2.78/GJ).		

Developer: **Information Source:**	Alternate Gas (original), then Southern Electric International, then Citicorp Industrial Credit. [Bridgwater, Appendix II page 99]
1. Background/History:	Gasifier construction started in 1985, in Florida by Alternate Gas Inc. The project ownership changed hands multiple times and then was relocated to Georgia and begin gasification processing in 1992.
2. Technology Description:	Wood gasification at to produce a LHV gas to fuel lime kilns. Wood is stored, screened, dried and then tranferred to one of two hoppers prior to injection into one of two fluidized bed gasifiers. The gasifiers are ~2.5 m in diameter and operate under atmospheric conditions between 650-800 ^{o}C.
3. Future Plans:	
4. Existing Process Data: Process type: Process size (I.e. pilot, commercial…): Feedstock:	 Bubbling Fluidized Bed Gasification Commercial Wood chips
Product: Yield (kg/kg wet feed): Use:	LHV gas 0.72 Lime kiln, boiler and drier fuel
Feedstock throughput (kg/h):	7400 (~200 ton/day)
Reactor conditions: Pressure (bar): Temperature (^{o}C):	 1 649-815
Reactant 1: Rate (kg/kg dry feed):	Hot air 1.45
Gaseous waste flowrate (kg/dg daf): Liquid waste flowrate (kg/kg feed):	0 592
5. Product: Hydrogen Carbon monoxide Carbon dioxide Methane C2+ Oxygen Nitrogen Chlorine Sulfur H$_2$O Other **Total**	Dry gas composition, volume % 12.67 15.5 15.88 5.72 2.27 n/a 47.85 0 0 0 0.1 100.0
Design gas output rate (m^3/h feed): Gas exit temperature (^{o}C): Heating value (MJ/m^3): Heavy metals content (mg/m^3): Particulate content (pilot test data) (g/m^3):	4845 745-801 5.62-8.25 n/a 2.3
6. Utilities:	*Air is supplied to each gasifier by 250 hp fans. Combined with a 500 hp drier fan, this accounts for the majority of the gasification system electrical load.
7. Costs: Capital: Operating: Product or Production Costs:	 $11.1MM $28,500/TPD $22.7/MBtu/h *electricity estimated to be between $15,000-$20,000 per month (at $0.04/kWh) Gas will be sold at Macon between $2.48-$2.64 (1992 dollars)/GJ.

Developer:	Sofresid/Caliqua (Designed by Ando-Torrax)
Information Source:	[Bridgwater, Appendix II page 93]
	[Reed]-- page 3-52
1. Background/History:	The Caliqua gasification system is based on a 1968 patent by Torrax Systems (USA).
	Six plants were constructed: Creteil, France; Florida, USA; Grasse, France; Japan;
	Luxembourg; Munich, Germany. Only the Cretil, France plant is still running.
2. Technology Description:	Municipal solid waste (MSW) is gasified in a fixed bed (updraft) gasifier at 8 tonne/h
	producing LHV gas to fuel a steam boiler for electricity production and district heating.
	Ash is produced and converted to slag.
3. Future Plans:	
4. Existing Process Data:	
Process type:	Fixed Bed Updraft Gasification
Process size (pilot, commercial…)	Commercial
Feedstock:	Municipal Solid Waste (MSW)
Product:	LHV gas
Yield (kg/kg daf feed):	n/a
Use:	Steam for district heating and electricity production
Feedstock throughput (kg/h):	8128 (215 ton/day)
Reactor conditions:	
Pressure (bar):	1
Temperature (^{o}C):	1300-1400
Reactant 1:	Hot air
Rate (m^3/h):	6000
Gaseous waste flowrate (kg/dg daf):	0
Liquid waste flowrate (kg/kg feed):	0
Solid waste flowrate, ash (kg/kg daf):	10
5. Product:	Dry gas composition, volume %
Hydrogen	n/a
Carbon monoxide	n/a
Carbon dioxide	n/a
Methane	n/a
C2+	n/a
Oxygen	n/a
Nitrogen	n/a
Chlorine	n/a
Sulfur	n/a
H_2O	n/a
Other	n/a
Design gas output rate (Nm^3/h feed):	n/a
Gas exit temperature (^{o}C):	n/a
Heating value (MJ/Nm^3):	n/a
Heavy metals content (define)(mg/Nm^3):	n/a
Particulate content (pilot test data) (g/Nm^3):	n/a
6. Utilities:	
7. Costs:	
Capital:	
Operating:	
Product or Production Costs:	

Developer:	Aerimpianti (subsidiary of Ansaldo)
Information Source:	[Bridgwater, Appendix II page 2]

1. Background/History:

The gasification plant was built by Aerimpianti. The circulating fluidized bed gasifiers are based on a Studsvik Energiteknik (Sweden) process and were designed by Aerimpianti under license from Studsvik.

2. Technology Description:

Between 90-202 ton/day of pelletized RDF is gasified which produces between 7000 and 200000 m^3/h of LHV gas that is used to fire a cement kiln or to produce steam for electricity.

The gasification plant consists of an RDF receiving, storage and feeding system, two circulating fluidized bed gasifiers, one process gas combustion and heat recovery system, steam turbine, and flue gas treatment system.

3. Future Plans:

4. Existing Process Data:

Process type:	Circulating Fluidized Bed Gasification
Feedstock:	Refuse Derived Fuel (RDF)
Product:	Low energy gas
Yield (kg/kg dry feed):	2.53
Use:	Cememt Kiln Firing
Feedstock throughput (kg/h):	1800-4200 (48-110 ton/day)
Reactor conditions:	
Pressure (bar):	0.5
Temperature (^{o}C):	850-900
Reactant 1:	Air
Rate (kg/kg dry feed):	1.7
Gaseous waste flowrate (m^3/h):	15000 - 43000
Liquid waste flowrate (kg/kg feed):	na
Solid waste flowrate, ash (kg/h):	270 - 630

5. Product:

	Volume % (Wet basis)		
Hydrogen	7-9	RDF Pellets:	80% paper
Carbon monoxide	9-13		10-15mm long
Carbon dioxide	12-14		5-10% moisture
Methane	Included in C2+		15% ash
C2+	6-9		16-17.5 MJ/kg heating value
Oxygen	-		
Nitrogen	47-52	From nitrogen purges into the system	
Chlorine (as HCL)	0.5-1.5 g/m^3		
Sulfur (as H_2S)	0.3-1 g/m^3		
H_2O	10-14		
Other	0.5-1.0		

Design gas output rate (Nm^3/kg feed):	1.94-3.33	
Gas exit temperature (^{o}C):	800-900	
Heating value (kJ/m^3):	4.5-5.5	Total gas energy at outlet = 7-8.5 MJ/m^3
Heavy metals content (mg/Nm^3):	na	
Particulate content (g/Nm^3):	30-50	
Tar content (g/Nm^3):	25-45	

6. Utilities:

7. Costs:

Capital:	na
Operating:	na
Product or Production Costs:	na

Developer:	Foster Wheeler (Formerly Ahlstrom)
Information Source:	[Bridgwater, Appendix II page 10]
	[Reed page 3-17]
1. Background/History:	FW is a commercial company with 12 years of boiler and gasification experience. FW Pyropower headquarters are located in San Diego and the boiler division in Finland. Equipment for the USA market is subcontracted and equipment for the European market is manufactured in Varkaus.
2. Technology Description:	The FW pyroflow gasifier is an atmospheric (1 atm) circulating fluidized bed gasifier that operates at ~1000^{o}C and is used for lime kiln heating. The gasifier is a refractory lined vertical cylinder that uses sand as the fluidizing agent. A cyclone is used to separate the sand from the gas exiting the unit and then is recycled back to the gasifier.
3. Future Plans:	
4. Existing Process Data:	
Process type:	Circulating Fluidized Bed Gasification
Process size (pilot, commercial......)	Commercial
Feedstock:	Wood
Product:	LHV Gas
Yield (kg/kg daf):	3.27
Use:	Lime kiln firing or electricity production
Feedstock throughput (kg/h):	600 (16 ton/day)
Reactor conditions:	
Pressure (bar):	1
Temperature (^{o}C):	905
Reactant:	Air
Rate (kg/kg feed):	1.7
Gaseous waste flowrate (kg/dg daf):	0
Liquid waste flowrate (from dryer scrubber):	0-10000 *tars
Solid waste flowrate, ash (kg/kg daf):	Minor
5. Product:	
Hydrogen	15-16
Carbon monoxide	21-22
Carbon dioxide	10-11
Methane	5-6
C2+	na
Oxygen	na
Nitrogen	46-47
Chlorine	-
Sulfur	0
H_2O	0
Other	na
Design gas output rate (m^3/h):	1181
Gas exit temperature (^{o}C):	700
Heating value (MJ/m^3):	7.5
6. Utilities:	
7. Costs:	
Capital:	na
Operating:	na
Product or Production Costs:	na

Developer:	Energy Products of Idaho (EPI, formerly JWP Energy Products)
Information Source:	[Bridgwater, Appendix II page 66]
	[Reed, page 3-27]

1. Background/History: EPI has a history of manufacturing both fixed bed updraft and fluidized bed gasifiers.

2. Technology Description: The aim of this process is the gasification of biomass in a fluidized bed gasifier for the production of a low heating value gas with a higher heating value of 4-6 MJ/Nm^3. The hot gas can be used with minimal cleaning to fuel steam biolers. System consists of a fuel storage area, fuel drier, feed hopper, fluidized bed gasifier (using air), boiler, and cyclone.

3. Future Plans: The three gasification plants installed (California, Missouri and Oregon) by EPI are not (1992) operational and future plans cancelled due to low fossil fuel prices.

4. Existing Process Data:

Process type:	Bubbling Fluidized Bed Gasification
Process size (pilot, commercial……)	Commercial
Feedstock:	Wood chips (30% moisture on wet basis, 5% ash, 17.55 MJ/kg heating value)
Product:	LHV gas
Yield (kg/kg daf):	3
Use:	Steam for power production
Feedstock throughput (kg/h):	4134 (110 ton/day)
Reactor conditions:	
Pressure (bar):	1
Temperature (^{o}C):	650
Reactant:	Air
Rate (kg/kg feed):	2
Gaseous waste flowrate (kg/dg daf):	none
Liquid waste flowrate (from dryer scrubber):	none
Solid waste flowrate, ash (kg/kg daf):	0.04

5. Product:

Hydrogen	5.80
Carbon monoxide	17.50
Carbon dioxide	15.80
Methane	4.65
C2+	2.58
Oxygen	0.80
Nitrogen	51.9
Chlorine	0
Sulfur	0
H_2O	0
Total	**99.0**

Design gas output rate (Nm^3/h):	8793
Gas exit temperature (^{o}C):	621.1
Heating value (MJ/Nm^3):	5.6
Heavy metals content (define)(mg/Nm^3):	-
Particulate content (pilot test data) (g/Nm^3):	na

6. Utilities:

7. Costs:

Capital:	$2.1MM $11,500 $27.2/TPD
Operating:	Estimated annual operating costs excluding feed costs in 1981 (350 days/year) were $685,200.00 Utilities 300 hp.
Product or Production Costs:	Wood chips were $20/ton

Developer:	ASCAB/Stein Industrie
Information Source:	[Bridgwater, Appendix II page 24]

1. Background/History: Basic gasifier research started in 1980 with a 100 kg/h fluidized bed gasifier. In 1983, plant was increased to 416 kg/h. In 1986, a 2500 t/h (60 t/d) pressurized fluidized bed sysetm was installed in France.

2. Technology Description: Production of syngas from wood chips for the eventual production of methanol or electricity. Woodchips are delivered a storage area, then hopper for stone removal, sizing, separation and drying to 15% wet basis in a rotary drum dryer. Fluidized bed material (calcined clay) is added to the feedstock prior to the feedstock entry into the gasifier to make up for bed material losses as a result of bed material removal for cleaning. Raw product gas from the gasifier passes into a secondary POX reactor where it reacts with additional oxygen at 1300 C decomposing any methane and converting entrained carbon and tars to gas.

3. Future Plans: Stein industrie has abandoned the process.

4. Existing Process Data:

Process type:	Bubbling Fluidized Bed Gasification
Process size (pilot, commercial….)	Pilot
Feedstock:	Wood chips (both eucalyptus and oak chips have been tested). 15% Moisture
Product:	Gas
Yield (Nm^3/kg feed):	1.36
Use:	Methanol production
Feedstock throughput (kg/h):	2000 (50 ton/day)
Reactor conditions:	
Primary reactor pressure (bara):	15
Primary reactor temperature (^{o}C):	700 - 750 (Mean was 716 C)
Secondary reactor pressure (bara):	15
Secondary reactor temperature (^{o}C):	1300
Reactant 1:	Steam
Rate (kg/kg feed):	0.4
Reactant 2:	Oxygen
Rate (kg/kg feed):	0.6
Gaseous waste flowrate (kg/dg daf):	n/a
Liquid waste flowrate (from dryer scrubber):	n/a
Solid waste flowrate, ash (kg/kg daf):	n/a

5. Product: Dry gas composition, volume %

Hydrogen	19.87
Carbon monoxide	25.3
Carbon dioxide	40
Methane	0
C2+	0
Oxygen	-
Nitrogen	13.42
H_2/CO ratio	0.76
CO/CO_2 ratio	0.65
Total	**100**
Design gas output rate (m^3/kg feed):	1.45
Gas exit temperature (^{o}C):	n/a
Heating value (MJ/m^3):	5.52
Heavy metals content (define)(mg/m^3):	n/a
Particulate content (pilot test data) (g/m^3):	<300

6. Utilties:

7. Costs:

Capital:	na
Operating:	na
Product or Production Costs:	na

Developer:	Tampella Power Inc., Finland
Information Source:	[Bridgwater, Appendix II page 114]
	[Reed, page 3-15]
1. Background/History:	The Tampella Power pilot plant is based on the U-Gas process developed at the IGT (now GTI). This plant was commissioned in Oct 1991, and is designed to operate using a coal feedstock and modifications were to be added in 1992 to enable biomass gasification.
2. Technology Description:	Goal is to gasify carbonaceous feedstocks in a 1800 kg/h pilot scale, pressurized fluidized bed gasifier for the production of a low heating value gas which can be used as a fuel for gas turbines. The pilot plant was designed for coal gasification and was modified for biomass gasification in 1992. The data from the pilot plant was to be used to design a commercial size plant.
3. Future Plans:	
4. Existing Process Data:	
Process type:	Bubbling Fluidized Bed Gasification
Process size (pilot, commercial….)	Commercial
Feedstock:	Coal
Product:	LHV Gas
Yield (kg/kg feed):	4.2
Use:	Boiler Fuel
Feedstock throughput (kg/h):	36400 (40 ton/day)
Reactor conditions:	
Pressure (bar):	20-23
Temperature (^{o}C):	850-950
Reactant 1:	Air
Rate (kg/kg feed):	0.4
Reactant 2:	Steam
Rate (kg/kg feed):	0.6
Gaseous waste flowrate (kg/dg daf):	0
Liquid waste flowrate (from dryer scrubber):	0
Solid waste flowrate, ash (kg/kg daf):	fluctuates
5. Product:	Results from a Wood Fuelled IGT U-Gas Gasifier at 20 bar (Results not from Tampella Pilot)
	Wet gas composition
Hydrogen	11.3
Carbon monoxide	13.5
Carbon dioxide	12.9
Methane	4.8
C2+	na
Oxygen	na
Nitrogen	40.2
H$_2$O	17.7
Total	**100.4**
Design gas output rate (kg/h):	9000
Gas exit temperature (^{o}C):	300-350
Heating value (MJ/Nm^3):	4-6
Heavy metals content (define)(mg/Nm^3):	na
Particulate content (pilot test data) (g/Nm^3):	na
6. Utilties:	
7. Costs:	
Capital:	$220.8MM $306,000/TPD $303/Mbtuh
Operating:	
Product or Production Costs:	

Developer:	Sydkraft AB (in co-operation with Foster Wheeler Energy International, Inc.)
Information Source:	[Bridgwater October,1999]
	[Reed page 3-77]

1. Background/History: Sydkraft AB has built the world's first complete IGCC Power Plant which utilizes wood as fuel. The plant is located in Varnamo, Sweden, and the technology used in the power plant is based on gasification in a pressurized fluidized bed gasifier. The plant generates 6 MW of electricity and 9 MW of heat for district heating. The goal was to demonstrate the technology rather than to run a fully optimized plant. Flexible and conservative solutions were chosen for the plant layout and design, to ensure the success of the project and to make the plant suitable for R & D activities.

2. Technology Description: The normal wood fuel is dried in a separate fuel preparation plant, using a flue gas dryer, to a moisture content of 5-20%, then pressurized in a lock hopper and fed to the gasifier by a screw feeder. Operating temp is 950-1000 C. Pressure is 18 bar(g) for gauge.
The gas generated is burned in the combustion chambers and expands through the gas turbine, generating 4 MW of electricity.
Hot flue gas from the gas turbine is ducted to the heat recovery steam generator (HRSG), where the steam generated, along with steam from the gas cooler, is superheated and then supplied to a steam turbine (40 bar, 455C).

3. Future Plans:

4. Existing Process Data:

Process type:	Circulating Fluidized Bed
Feedstock:	Wood fuels
Product:	LHV Gas
Yield (kg/kg wet feed):	
Use:	Power and steam
Feedstock throughput:	18 MW

Reactor conditions:

Primary reactor pressure (bar):	18
Primary reactor temperature (^{o}C):	950-1000

Reactant 1:	Air-10% of the air is extracted from the gas turbine compressor
Rate (kg/kg dry feed):	na

5. Product: Dry gas composition, volume %

Hydrogen	9.5-12	Slightly lower than predicted
Carbon monoxide	16-19	
Carbon dioxide	14.4-17.5	
Methane	5.8-7.5	Slightly higher than predicted, therefore heating value is maintained.
C2+		
Oxygen		
Nitrogen	48-52	
Chlorine		
Sulfur		
H_2O		
Other		

Design gas output rate (Nm^3/h feed):	
Gas exit temperature (^{o}C):	
Heating value (MJ/Nm^3):	5.3-6.3
Heavy metals content (mg/Nm^3):	
Particulate content (pilot test data) (g/Nm^3):	

6. Utilities:

7. Costs:

Capital:	na
Operating:	na
Product or Production Costs:	na

Developer:	BECON (Biomass Energy Conservation Facility) at Iowa State University
Information Source:	"Design, Start-up, and Operation of a 5 ton/day Fluidized Bed Biomass Gasifier"
1. Background/History:	Goal of the ISU project was to commercially develop several niche markets for biomass heat and power in the state of Iowa. A gasification facility (BECON) has been constructed that is capable of evaluating a variety of biomass feedstocks.
2. Technology Description:	The BECON fluidized bed gasifier is nominally rated at 2 to 3 MM Btu/hr. This capacity corresponds to an average feed rate of 400 lb/hr for a fuel with a HHV fo 7000 Btu/lb. During gasification, the reactor is operated in a fuel rich environment where only about 25-30% of the oxygen necessary for complete combustion is supplied. In recent experiments the HHV of the producer gas was 120 Btu/scf, carbon conversion was 85%.
3. Future Plans:	Redesign the material handling system to accommodate a wide variety of feedstocks.

4. Existing Process Data:

Process type:	Bubbling Fluidized Bed
Feedstock:	Shelled Corn
Product:	LHV Gas
Yield (kg/kg wet feed):	na
Use:	na
Feedstock throughput (kg/h):	182 (5 ton/day)

Reactor conditions:

Pressure (bar):	1
Temperature (^{o}C):	730

Reactant 1:	Air
Rate (scfm):	110

Gaseous waste flowrate (kg/dg daf):
Liquid waste flowrate (kg/kg feed):
Solid waste flowrate, ash (kg/kg daf):

5. Product:

Hydrogen	4.1
Carbon monoxide	23.9
Carbon dioxide	12.8
Methane	3.1
C2+	
Oxygen	0.2
Nitrogen	55.9
Chlorine	
Sulfur	
H$_2$O	
Total	**100.0**

Design gas output rate (scfm):	~200
Gas exit temperature (^{o}C):	
Heating value (MJ/Nm^3):	4.5
Heavy metals content (mg/Nm^3):	
Particulate content (pilot test data) (g/Nm^3):	

6. Utilities:

7. Costs:

Capital:	
Operating:	
Product or Production Costs:	

Appendix B: Follow-Up Technolgies

Following is a list of gasification technologies that were identified during preparation of this analysis but were accompanied by insufficient data to include in the analysis. They are large-scale, commercially proven, and recently (>1995) commissioned. The list was extracted from a database provided at http://www.woodgas.com.

Organization	Type	Feedstock(s)	Purpose	Misc.
1. Ankur	FB-downdraft	Wood, rice hulls	Power & Steam	India
2. BIOSYN	BFB	Wood	Methanol prod.	Canada; O_2 used
3. Renewable Energy Corporation	FB	Wood, paper, bark, agricultural waste	Power & Steam	Australia
4. Power Gasifiers International	FB-downdraft	Wood	Power production	UK
5. PrimeEngergy	FB-cocurrent	Rice husks, straw, bark, wood	Power production	USA
6. SUR-LITE	FB	Wood, cotton waste,	Power & Steam	USA
7. Thermoselect	FB	MSW, sludge, medical waste	Waste management	Switzerland, O_2 gasifier
8 BIVKIN	CFB	Wood, waste	Fuel Gas	Netherlands
9. Cratech	FB	Cotton waste	Fuel Gas (turbine)	USA, pressurized

Appendix C: Summary Data Tables in English Units

Table 2. Potential Biomass Gasifier Feedstocks

	Ultimate Analysis (wt% dry basis)						Proximate Analysis (wt% dry basis)			
	C	H	N	O	S	Ash	Moisture	Volatiles	Fixed Carbon	Heating Value HHV (Btu/lb)
Agricultural Residues										
Sawdust	50	6.3	0.8	43	0.03	0.03	7.8	74	25.5	8,315
Bagasse	48	6.0	-	42	-	4	1	80	15	7,323
Corn Cob	49	5.4	0.4	44.6	-	1	5.8	76.5	15	7,323
Short Rotation Woody Crops										
Beech Wood	50.4	7.2	0.3	41	0	1.0	19	85	14	7,926
Herbaceous Energy Crops										
Switchgrass	43	5.6	0.5	46	0.1	4.5	8.4	73	13.5	6,634
Straw	43.5	4.2	0.6	40.3	0.2	10.1	7.6	68.8	13.5	7,323
Miscanthus	49	4.6	0.4	46	0.1	1.9	7.9	79	11.5	5,170
Municipal Solid Waste										
Dry Sewage	20.5	3.2	2.3	17.5	0.6	56	4.7	41.6	2.3	3,446
Coals										
Subbituminous	67.8	4.7	0.9	17.2	0.6	8.7	31.0	43.6	47.7	10,598
Bituminous	61.5	4.2	1.2	6.0	5.1	21.9	8.7	36.1	42.0	11,632

Table 6. Individual Gasifier Operating Conditions
(English Units)

	EPI	Stein	Tampella	ISU	GTI	SEI	Purox	Sofresid
Type	BFB	BFB	BFB	BFB	BFB	BFB	FB	FB
Primary Feedstock	Wood	Wood	Wood	Corn	Wood	Wood	MSW	MSW
Throughput (Ton/day)	110	66	50	5	13	200	200	215195
Pressure (psia)	14	218	290-334	14	508	14	14	14
Temperature (^{o}F)	1200	1,292-1,382	1,562-1,742	1,346	1,500	1,200-1,500	-	2,372-2,552
Reactant 1	Air	O_2	Air	Air	O_2	Air	O_2	Air
Input (lb/lb feed)	2.0	0.6	0.4	-	0.27	1.45	-	-
Reactant 2	-	Steam	Steam	-	Steam	-	-	-
Input (lb/lb feed)	-	0.4	0.5	-	0.64	-	-	-
Gas Output (ft^3/h)	317,584	102,412	-	-	11,830	171,100	-	1,199,286
Exit Temperature (^{o}F)	1150	-	572-662	-	1,500	1,472	-	-
Heating Value (MMBtu/ft^3)	168	165	120-180	135	389	170	-	237
	TPS	Aerimp-ianti	Foster Wheeler	Lurgi	Sydkraft	BCL/FERCO[a]	MTCI[b]	
Type	CFB	CFB	CFB	CFB	CFB	CFB	BFB	
Primary Feedstock	Wood	RDF	Wood	Bark	Wood	Wood	Pulp	
Throughput (Ton/day)	10	50-110	16	93-120	-	26.5	7.8	
Pressure (psia)	15	15	15	1	261	15	51	
Temperature (^{o}F)	1293-1742	1562-1652	1652	1472	1742-1832	1112-1832	1454-1500	
Reactant 1	Air	Air	Air	Air	Air	Air	-	
Input (lb/lb feed)	-	1.7	1.7	1.25	-	0.08	-	
Reactant 2	-	-	-	-	-	Steam	Steam	
Input (lb/lb feed)	-	-	-	-	-	0.31	2.2	
Gas Output (ft^3/h)	-	123,550-494,200	41,689	342,410-441,250	-	28240	-	
Exit Temperature (^{o}F)	-	1472-1652	1292	1112	-	1508	-	
Heating Value (MMBtu/ft^3)	120-210	134-165	224	174	150	538	500	

Table 7. Gasifier Operating Conditions Summary
(English Units)

	BFB Range	CFB Range	Fixed Bed Range	BCL/ FERCO[a]	MTCI[b]	Shell[c]
Feedstock	Various	Various	Various	Wood	Pulp	Coal
Throughput (Ton/day)	5-200	10-120	200-215	25.5	7.8	2,375
Pressure (psia)	15-508	15-276	15	15	15	435
Temperature (^{o}F)	662-1742	1472-1832	2372-25520	1112-1832	1454-1500	2552
Reactant 1	O_2 or Air	Air	O_2 or Air	Air	-	O_2
Input (lb/lb feed)	0.4-2.2	1.25-1.7	-	0.08	-	0.98
Reactant 2	Steam	-	-	Steam	Steam	Steam
Input (lb/lb feed)	0.5-0.64	-	-	0.31	2.2	~0
Gas Output (ft^3/h)	11,826-310,393	41,689-441,250	1.19x10^6	28,240	-	50.2×10^6
Exit Temperature (^{o}F)	572-1472	1112-1652	-	1508	-	464
Heating Value (MMBu/ft^3)	120-389	120-224	237	538	500	284

Table 8. Compositions of Biomass-Derived Syngas
(English Units)

	EPI[a]	Stein	Tampella	ISU	GTI	SEI	Purox
Type	BFB	BFB	BFB	BFB	BFB	BFB	FB
Feedstock	Wood	Wood	Wood	Wood	Wood	Wood	MSW
H_2	5.8	19.9	11.3	4.1	14.8	12.7	23.4
CO	17.5	26.2	13.5	23.9	11.7	15.5	39.1
CO_2	15.8	40.3	12.9	12.8	22.39	15.9	24.4
H_2O	dry	dry	17.7	dry	dry	dry	dry
CH_4	4.65	-	4.8	3.1	10.8	5.72	5.47
C_2+	2.58	-	-	-	0.13	2.27	4.93
Tars	-	0.11	-	-	0.27	-	(in C_2+)
H_2S	-	-	-	-	0.01	-	0.05
O_2	-	-	-	0.2	-	-	-
NH_3	-	-	-	-	0.10	-	-
N_2	51.9	13.4	40.2	55.9	40.3	47.9	-
H_2/CO Ratio	0.3	0.8	0.8	0.2	1.6	0.8	0.6
Heating Value ($MMBtu/ft^3$)	167	164	120-180	134.5	389	167	-

	TPS	Aerimp-ianti	Foster Wheeler	Lurgi	Sydkraft	BCL/FERCO[a]	MTCI[b]
Type	CFB	CFB	CFB	CFB	CFB	CFB-other	BFB-other
Feedstock	RDF	RDF	Wood	Bark	Wood	Wood	Pulp
H_2	7 – 9	7-9	15-17	20.2	11	14.9	43.3
CO	9 – 13	9-13	21-22	19.6	16	46.5	9.22
CO_2	12 – 14	12-14	10-11	13.5	10.5	14.6	28.1
H_2O	10 – 14	10-14	dry	dry	12	Dry	5.57
CH_4	6-9	6-9	5-6	(in C_2+)	(in C_2+)	17.8	4.73
C_2+	-	-	-	3.8	6.5	6.2	9.03
Tars	-	0.5-1	-	<1g/m^3	(in C_2+)	-	Scrubbed
H_2S	-	-	-	Very low	-	-	0.08
O_2	-	-	-	-	-	0	0
NH_3	-	-	-	-	-	0	0
N_2	47 - 52	47-52	46-47	42.9	44	0	0
H_2/CO Ratio	0.7	0.7	0.7	1.0	0.7	0.3	4.6
Heating Value ($MMBtu/ft^3$)	120-210	134-165	224	174	150	538	500

Table 9. Syngas Compositions Summary
(English Units)

Feedstock	BFB Range	CFB Range	BCL/FERCO[a]	MTCI[b]	Fixed Bed	Shell[c]
	Various	Various	Wood	Pulp	MSW	Coal
H_2	5-26	7-20	14.9	43.3	23.4	24
CO	13-27	9-22	46.5	9.22	39.1	67
CO_2	12-40	11-16	14.6	28.1	24.4	4
H_2O	<18	10-14	dry	5.57	dry	3
CH_4	3-11	<9	17.8	4.73	5.47	0.02
C_2+	<3	<4	6.2	9.03	4.93	0
Tars	<0.11	<1	-	Scrubbed	-	0
H_2S	~0	~0	-	0.08	0.05	1
O_2	<0.2	0	0	0	-	0
NH_3	0	0	0	0	-	0.04
N_2	13-56	46-52	0	0	-	1
H_2/CO Ratio	0.2-1.6	0.6-1.0	0.3	4.6	0.6	0.36
Heating Value ($MMBtu/ft^3$)	120-389	120-224	538	500	237	284

Table 11. Gasification Capital Costs
(English Units)

Technology Type	Type	Size (Ton/day)	Capital Cost ($ 10^6$)	Capital Cost ($ 10^3$ /TPD)	Capital Cost ($/10^9$Btu/h Syngas)
BFB Range [9,13]	BFB	187-1058	2-36	12-41	20.5-52.0
BFB Average [9,13]	BFB	678	16.1	22.7	28.0
BCL/FERCO[a] [9,11,22]	CFB	846-1003	18-26	22.2-25.8	31.2-45.5
MTCI[b] [9]	BFB	48.5	1.1	23.1	-
Shell Coal Gasifier[c]	-	2425	80.5	33.8	1.33