once-through boiler with steam conditions of 125 kg/s (275.6 lb/s), 540 °C (1004 °F)/17,000 kPa (2,466 psi) and 540 °C (1004 °F)/4,000 kPa (580 psi) reheat.

Table 5. Specifications of the Gasification Plant at Lahti, Finland

Design Capacity	Boiler	167 MW_e
		240 MW_{th}
	Gasifier	45 MW_{th}
Fuels (GWh/a thermal)	Coal	1200
	Natural Gas	800
	Biomass	ca. 300

The goal of the integrated gasification plant was to demonstrate the commercial scale of direct gasification of wet biofuel and the use of hot, raw and very low caloric gas directly in the existing coal-fired boiler. The gasifier is an atmospheric circulating fluidized-bed (CFB) gasification system. The biofuel contains 20-60% water with 40-80% combustibles and 1-2% ash. Feedstocks include biomass (wood chips, bark, sawdust), REF (recycled refuse), railway sleepers (chipped onsite), shredded tires, plastics, etc. The biofuels are not dried, and this reduces the investment costs and simplifies the overall system.

The operating temperature in the reactor varies from 800 to 1,000 °C (1,472-1,832 °F) depending on the biofuel and application. The primary reaction is pyrolysis of the biofuel followed by a secondary homogeneous reaction taking place in the gas phase. Most of the solids in the system are separated in the cyclone and returned to the lower part of the gasifier reactor.

During the first year of operation, about 230 GWh of energy was generated from biomass. A total of 4,730 hours of operation was performed in the gasification mode in 1998. The highest monthly availability was 93%, and the average availability was 82%. A 5-10% reduction of NO_x (10 mg/MJ or 0.0236 lb/mmBtu) and 20-25 mg/MJ (0.0465-0.0582 lb/mmBtu) in SO_x were obtained. However, an increase of about 5 mg/MJ (0.0118 lb/mmBtu) of HCl was obtained because of the presence of chlorine in the REF. The trace metals were also increased in the emission. There were no major problems reported with the operation of the gasification plant (Ståhl,, 1999).

1.1.2.1.3 Bioflow Pressurized Circulating Fluidized-Bed Gasifiers

The Swedish power company, Sydkraft AB, decided in June 1991 to build a co-generation plant at Värnamo, Sweden to demonstrate the integrated gasification combined cycle (IGCC) technology. Bioflow, Ltd., was formed as a joint venture between Ahlstrom and Sydkraft in 1992 to develop the pressurized air-blown circulating fluidized-bed gasifier. Foster Wheeler acquired the part of Ahlstrom that built the gasifie,r and Bioflow became part of Foster Wheeler in 1995. The biomass integrated gasification combined cycle (BIGCC) plant in Värnamo was commissioned in 1993 and fully completed in 1996. It generates 6 MW_e and 9 MW_{th} for district heating in the city of Värnamo. This was the first complete BIGCC for both heat and power from biomass (Ståhl, 1997; Engström, 1999; and Ståhl, 1999).

The flow diagram of the Bioflow IGCC at Värnamo is shown in Figure 21.

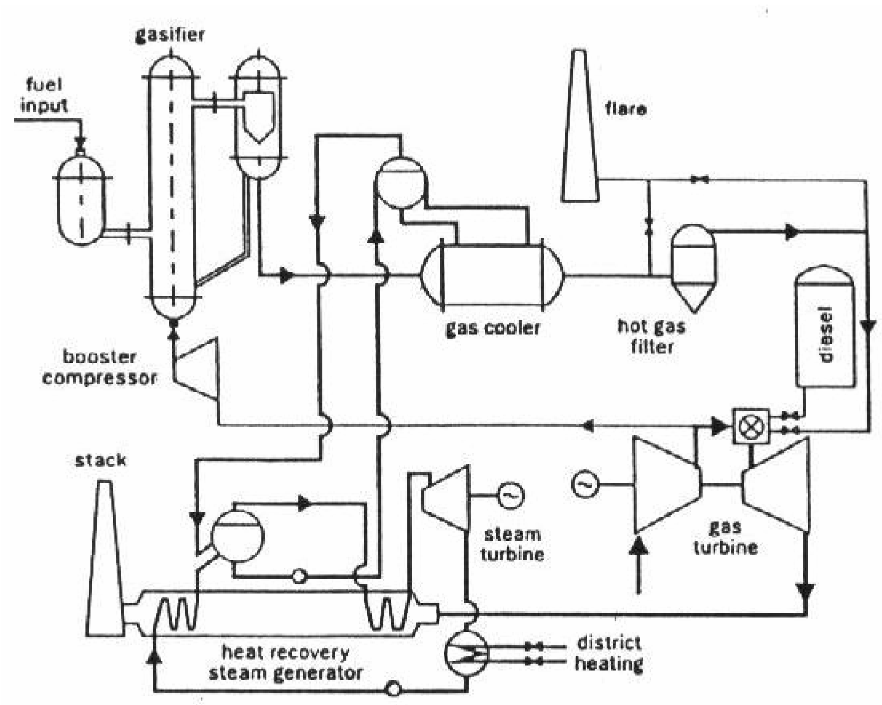

Figure 21. BIGCC at Värnamo, Sweden based on the Bioflow Gasifier (Ståhl, 1999)

In this process, the wood fuel is dried to 10-20% moisture in a separate fuel preparation plant using a flue gas dryer. It is pressurized in a lockhopper system and fed to the gasifier by screw feeders a few meters above the bottom. The operating pressure and temperature of the gasifier are 2,000 kPa (290 psi) and 950-1,000 °C (1,742-1,832 °F), respectively. The gasifier consists of the fluidized-bed reactor, cyclone, and cyclone return leg, all totally refractory lined. The gas produced from the system flows to a gas cooler and a hot gas filter after passing through the cyclone. The gas cooler lowers the gas temperature to 350-400 °C (662-752 °F) before it enters the ceramic filter system. The gas is burned in the combustion chambers and expands through the gas turbine generating 4 MW_e. The gas turbine is a single-shaft industrial gas turbine supplied by Alstom Gas Turbine (Typhoon). The system was designed for low heating value gas (5 MJ/Nm^3 or 134 Btu/scf). Heat is recovered by the heat recovery steam generator (HRSG) to produce an additional 2 MW of electricity.

Table 6 shows the technical data from the Värnamo BIGCC plant (Ståhl, 1997).

Table 6. Technical Data for Värnamo BIGCC Plant (Ståhl, 1997)

Component	Specification
Power Generation	6 MW_e
Heat Generation	9 MW_{th}
Fuel Input	18 MW (85% ds)
Fuel	Wood Chips
Net Electrical Efficiency (LCV)	32%
Total Net Efficiency (LCV)	83%
Gasification Pressure	2,000 kPa (290 psi)
Gasification Temperature	950-1,000 °C (1,742-1,832 °F)
Lower Calorific Value of Product Gas	5 MJ/Nm^3 (134 Btu/scf)
Steam Pressure	4,000 kPa (580 psi)
Steam Temperature	455 °C (851 °F)
Plant Owner	Sydkraft AB

The commissioning of the feed preparation plant was in late 1992. The first gasification test on wood chips at low pressure was preformed in June 1993. The start-up phase was completed during spring 1996. As of August 1999, a total of 8500 hours of gasification runs had been perfromed with about 3,500 hours of operation as a fully integrated plant. Feedstocks such as wood chips, forest residue (bark, branches, etc), sawdust and bark pellets, willow (salix), straw and pelletized RDF have been processed at the plant. They all showed good results without deposits or sinter in the systems. The bed material of the gasifier is magnesite (MgO) which performed well. Other materials could be tested to further optimize the gasification process.

The hot-gas cleanup was originally carried out with a ceramic filter that was supplied by Schumacher GmbH. The filter candles were arranged in six groups, with separate backpulsing. Initially, the ceramic filter showed good filter efficiency with stable pressure drop. However, two ceramic candles broke after more than 1,200 hours of trouble-free operation. The reason for the breakage was never identified by the manufacturer. A new design of ceramic filters was installed, but one of the new candles broke only after 350 hours of operation. Several modifications were made, and a metallic police filter was installed downstream of the main filter. The main filter failed soon after the modifications. The ceramic filter candles were replaced by metallic filter candles during the summer of 1998. The metallic filter was supplied by Mott Corporation. The new metallic filter has been operated more than 2,200 hours as of 1999 without any breakage or other damage during normal operation (Ståhl, 1999).

The dry gas composition of the product gas is shown in Table 7. The gas quality regarding hydrogen was lower than expected. The gas heating value was in the range of 5.3-6.3 MJ/Nm^3 (142-169 Btu/scf). The benzene and light tars concentrations for bark and pine chips are shown in Table 8. The benzene and light tars were lower with bark as compared to pine chips.

Table 7. Product Gas Composition from the BIGCC at Värnamo, Sweden

Gas Component	Concentration (vol. %)
CO	16-19%
H_2	9.5-12%
CH_4	5.8-7.5%
CO_2	14.4-17.5%
N_2	48-52%

Table 8. Benzene and Light Tars Concentrations

Fuel	Benzene, mg/Nm^3	Light Tars, mg/Nm^3
Bark (60%), Forest Residues (40%)	5,000-6,300	1,500-2,200
Pine Chips	7,000-9,000	2,500-3,700

The thermal NO_x was low due to the relatively low combustion temperature in the gas turbine combustors. The level is a direct function of the level of nitrogen content in the feedstock. With high nitrogen content fuel such as bark, the NO_x level was around 130 ppm. A NO_x level of 40 ppm was recorded from low nitrogen content fuel. The NO_x level can be reduced by developing new combustors, and the use of selective catalytic oxidation (SCO) can further reduce the emissions from ammonia and HCN. The recorded levels of alkalines were below 0.1 ppm (wt.) (Ståhl, 1999).

1.1.2.2 Battelle High-Throughput Gasification Process (BHTGP)

Batelle Memorial Laboratory demonstrated high-throughput gasification in cooperation between the U.S Department of Energy, the National Renewable Energy Laboratory (NREL), Burlington Electric Department, and the Future Energy Resources Corporation (FERCO) (Bain, 1996). The project for IGCC demonstration began in August 1994. The demonstration was located at the McNeil wood-fired power plant in Burlingtion, Vermont. The power plant has a capacity of 50 MW_e and was built in 1984. The capital cost of the plant was $67 million (1984) and was $13 million below budget. It is owned by the Burlington Electric Department, Central Vermont Public Services Corp., Green Mountain Power Corp., and the Vermont Public Supply Authority. A total of 77.1 metric ton/h (85 ton/h) of wood chips can be processed.

The Battelle High-Throughput Gasification Process (BHGTP) system uses a low-pressure indirectly heated biomass gasifier. It has been demonstrated successfully in a 9.1 metric ton/day (10 ton/day) Process Research Unit (PRU) at Battelle's Columbus Laboratories in West Jefferson since 1980. This system was designed especially for biomass to take advantage of its high reactivity, low ash, low sulfur, and high volatile matter content. It has operated for over 22,000 hours. FERCO of Atlanta, Georgia, has licensed the technology from Battelle. The gasifier will be operated as an IGCC eventually and includes heat recovery and a condensing steam turbine. The plant is 20 times the scale of the pilot plant that can process 181.4 metric ton/h (200 ton/h) of woody feedstock. It accounts for about 30% of the plant's load (Bain, 1996).

The first phase of design and construction was completed in 1998 by Zurn NEPCO of Portland, Maine, and Redmond, Washington. The second phase includes the start-up and shake-down testing which began in 1998 and continued through 1999. The final phase involves long-term operation and testing. A gas turbine was designed and installed during the final phase in 2000. The other companies and agencies that are evaluating the technologies include Weyerhaeuser, General Electric, International Paper, Centerior Energy, the State of Iowa, New York State Energy Research and Development Authority, and the U.S. Environmental Protection Agency.

FERCO has trademarked the process SilvaGas™ (January 2001). The SilvaGas™ process uses two physically separated, circulating fluidized-bed reactors. One reactor acts as a gasification reactor to convert the biomass to gas and residual char. The second reactor is a combustion reactor which burns the char to provide heat for gasification. Figure 22 shows a schematic diagram of the gasification system.

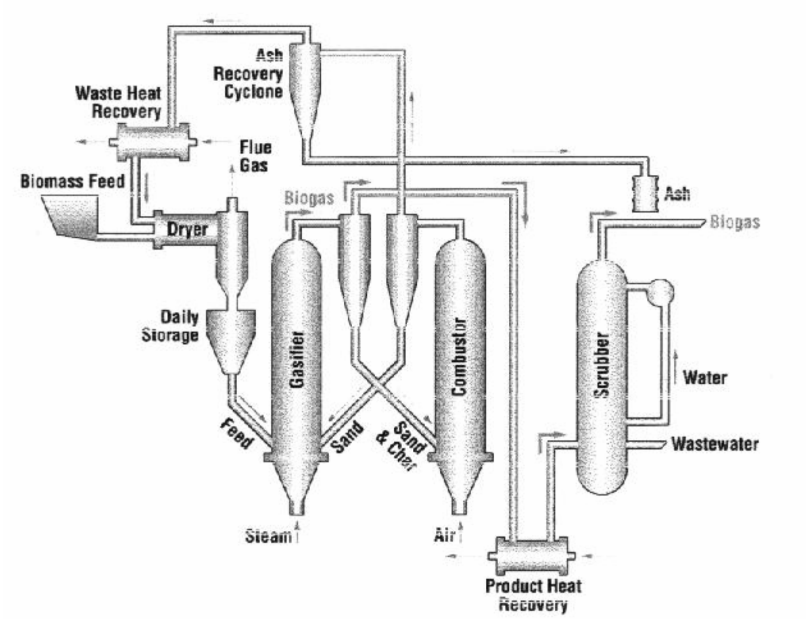

Figure 22. FERCO's SilvaGas™ Process at Burlington, Vermont

One system was installed at McNeil generating station in Burlington, Vermont. The flow diagram of the Battelle/FERCO IGCC at McNeil generating station is shown in Figure 23. Some plant statistics for the Burlington installation are shown in Table 9.

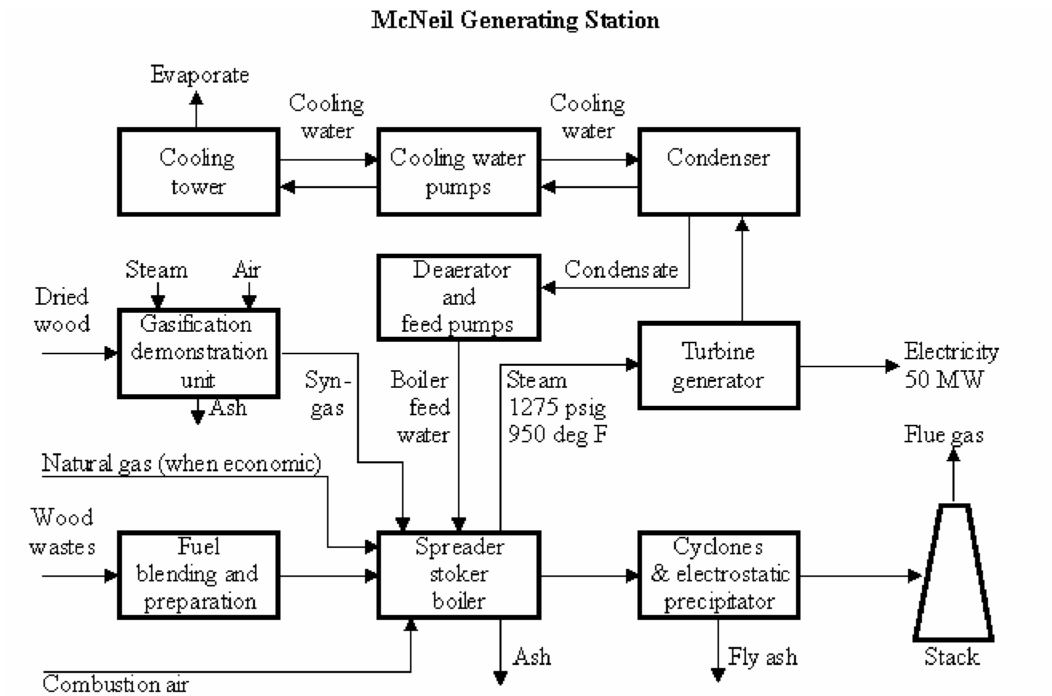

Figure 23. Flow Diagram of the Battelle/FERCO IGCC at McNeil Generating Station.

Table 9. Statistics of the Burlington Biomass Gasification Plant

Component	Specification			
Design Capacity, MW_e	50			
Configuration	Traveling grate stoker boiler			
Fuels	Wood wastes: forest, mill, and urban residues, Natural Gas (when economical)			
Year	1995	1996	1997	1998*
Net generation, MWh/a	136,000	137,000	155,000	155,000
Annual capacity factor, %	31.0	31.1	35.4	35.4
Net heat rate, MJ/kWh (Btu/kWh)	14.47-14.9 (13,714-14,125)			
Thermal Efficiency, HHV, %	24.-24.9			
* Projected in 1998				

In the FERCO process, the wood is heated to about 830 °C (1,526 °F) by hot sand circulating between two chambers. The gas has a medium heat content of about 18.6 MJ/m^3 (500 Btu/ft^3). This can be used as fuel for unmodified gas turbine. Since this gasifier does not require pure oxygen feed and produces medium heat-content gas, it is less costly to build and operate according to FERCO. The gasifier design has a high throughput of 3,000 lb biomass/h per ft^2 of cross sectional area of the reactor compared to about 200 lb/h-ft^2 for a conventional gasifier. The gasifier has a diameter of 1.07 m (3.5 ft) with a design capacity of 181.4 metric ton/day (200 ton/day) dry wood. The plant tested two gas conditioning systems for tar removal. The first system was a conventional scrubbing system with a venturi scrubber followed by a spray tower scrubber which removed most of the tars. The second system was a fluidized-bed catalyst chamber employing a new catalyst called DN-34. This essentially eliminated all tars from the gas. The gas was conditioned and pressurized to 100 psig to fire a gas turbine. A pilot test demonstrated the operation of a Solar Turbine 200 kW conventional gas turbine-generator with an unmodified gas turbine for gasification. A comparison of the gas quality is shown in Table 10.

Table 10. Comparison of Data from the PRU and McNeil Station (Paisley, 2001)

Component	Volume Percent	
	PRU Data	McNeil Station Data
H_2	17.5	22.0
CO	50.0	44.4
CO_2	9.4	12.2
CH_4	15.5	15.6
C_2H_4	6.0	5.1
C_2H_6	1.1	0.7
HHV, MJ/Nm^3 (Btu/scf)	18.5 (499)	17.3 (468)

The gasification demonstration plant has not operated continuously for a sustained period of days or weeks for the 18 months after the completion of the construction. One major change was made to the gasifier in late 1998; however, the specific problems have not been disclosed. The Salix project with planting of 5,000 short rotation energy crop trees to supply the power plant at McNeil site was uncertain. The first lesson learned from the project was a siting problem because of its urban setting. The second problem was the long-term fuel contracts resulting in a pile up of wood at the site and deterioration of the wood when the plant was not operated (www.westbioenergy.org).

The latest data presented at the ASME conference in New Orleans reported that the throughput of the gasifier was in excess of 317.5 metric ton/day (350 ton/day) over the design capacity of 181.4 metric ton/day (200 ton/day) of the plant. The FERCO website has claimed a throughput of 408.2 metric ton/day (450 ton/day). The planning for the next 12 months will further evaluate the gas conditioning, design and implementation of advanced power generation, and the options of biomass drying at the site (Paisley, 2001). The capital investment for a conceptual 56 MW_e plant is $1,307/kW (1996 dollars) according to FERCO.

FERCO was reorganized and refinanced in 1999 with the addition of the Turner Foundation as a shareholder (Paisley, 2001). Turner Foundation and private investors have provided $16 million to FERCO to commercialize FERCO's biomass gasification technology (Electric Light & Power 78, no. 4, p. 26, Apr. 2000).

The Battelle/FERCO gasification plant was scheduled for start up during the summer of 2001 with additional analytical support from NREL (person communication with Ed Wolfrum).

1.1.2.3 GTI Pressurized Fluidized-bed Gasifier (Renugas®)

GTI has developed the Renugas® biomass gasification technology based on their success in the U-Gas® coal gasification technology and holds US Patents 4,592,762 and 4,699,632. The PDU gasifier has a dimension of 0.91-m O.D. x ~6.7-m (3-foot O.D. x ~22-foot) height and has a Incoloy 800H metal liner. The fluidization section is about 1.8-2.3 m (6-7.5 ft) in height. An isometric view of the 12 ton/day PDU is shown in Figure 24.

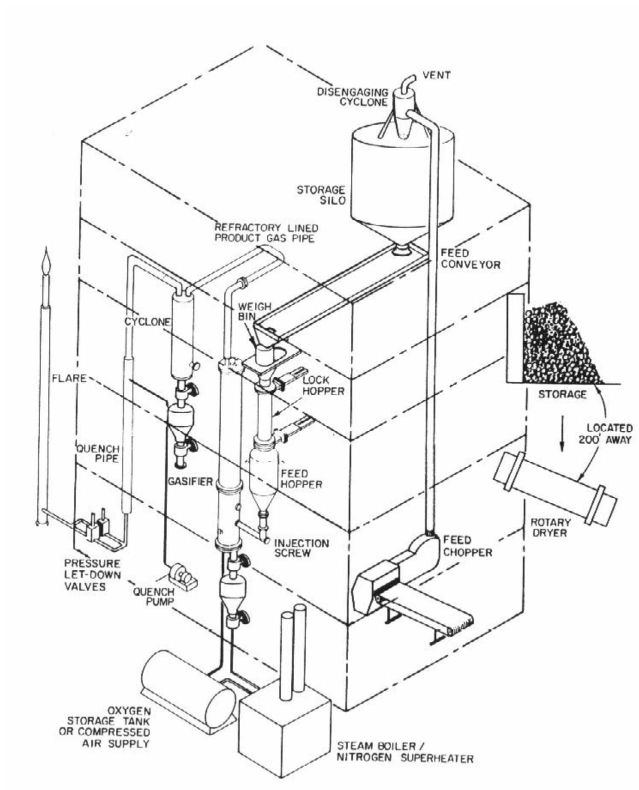

Figure 24. Isometric View of the 12 tpd GTI PDU

Bagasse, wood chips, whole tree chips, hard and soft woods, willow, rice and wheat straw, alfalfa, highway chippings, mixture of bark and pulp sludge, and pelletized RDF were all tested with the 10.9 metric ton/day (12 ton/day) PDU at GTI in Chicago. The conditions of the gasifier are summarized in Table 11.

Table 11. Operating Conditions of Renugas® PDU Gasifier

Parameter	Conditions
Temperature, °C (°F)	748-982 (1,380-1,800)
Pressure, kPa (psi)	up to 2,413 (350)
Feed Rate, kg/h (lb/h)	181-472 (400-1,040)
Feed Moisture, %	5-27
Steam Input, lb/lb feed	0-1.2
Fluidized Bed Height, m (ft)	1.83-2.29 (6-7.5)

Superficial Gas Velocity, m/s (ft/s)	0.46-1.37 (1.5-4.5)

1.1.2.3.1 Renugas® Hawaii Biomass Gasifier Project

The objective of the Hawaii Biomass Gasifier Project is to scale-up the pilot 10.9 metric ton/day (12 ton/day) GTI's Renugas® pressurized air/oxygen gasifier to 45.4-90.7 metric ton/day (50-100 ton/day) using bagasse and wood as fuel. This would demonstrate the near-term integration gasification and hot-gas cleanup (HGCU) system with gas turbines for power and heat generation.

The participants of this projects are Westinghouse Electric Corporation, the Pacific International Center for High Technology Research (PICHTR), the Hawaii Natural Energy Institute (HNEI), the Hawaii Commercial and Sugar Company (HC&S), the Ralph M. Parsons Company, and the National Renewable Energy Laboratory.

The biomass gasification demonstration plant is located at a site adjacent to the Hawaiian Commercial and Sugar Company (HC&S) on the island of Maui. The Renugas® gasifier was designed to operate with either air or oxygen at pressures up to 2,068 kPa (300 psia) with typical temperatures of 850 to 900 °C (1,562-1,652 °F). Phase one of the project included the design, construction, and preliminary operation of the gasifier. Phase two of the project would operate the gasifier at a feed rate of 45.4 metric ton/day (50 ton/day) at a maximum pressure of 1,034 kPa (150 psia). A slip-stream HGCU unit would be installed to provide long-term evaluation of its performance. A full-scale HGCU would be designed, and a gas turbine would be added to the system to generate 3-5 MW of electricity at 91.7 metric ton/day (100 ton/day) capacity. Phase three of the project would operate the gasifier in oxygen-blown mode to produce a syngas for methanol synthesis in addition to electricity generation.

A schematic diagram of the Renugas® gasifier is shown in Figure 25, and the schematic diagram of the demonstration plant is shown in Figure 26.

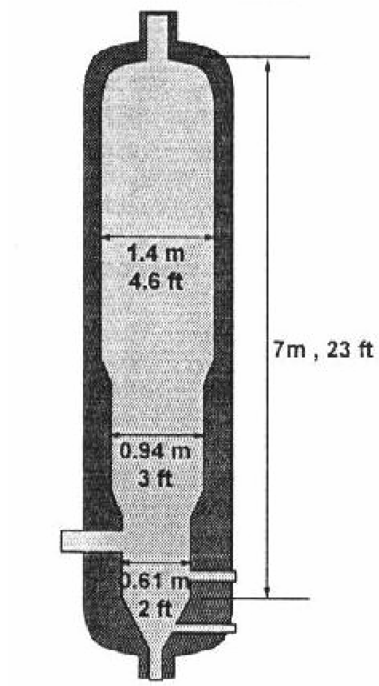

Figure 25. GTI Demonstration Plant Gasifier

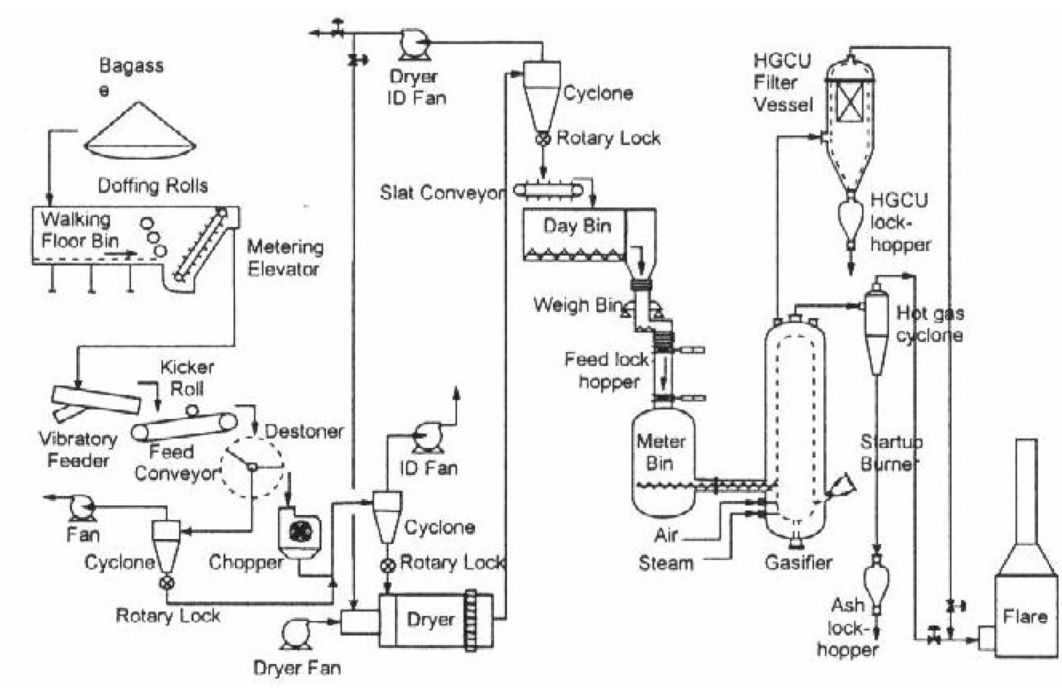

Figure 26. Renugas® Demonstration Plant in Paia, Hawaii

The Renugas® demonstration gasifier has a dimension of 1.4 m I.D. x 7.0 m (4.6 feet I.D. x 23 feet) in height. The lower fluidized-bed section has an internal diameter of 0.914 m (3 ft). The overhead expansion zone has an internal diameter of 1.4 m (4.6 ft). The gasifier was packed with fiber insulation in order to operate it at adiabatic condition.

Spherical alumina beads were used to provide good heat transfer and fluidization. The biomass was fed at the lowest part of the fluidized-bed reactor.

The bagasse was reduced to approximately ½- to 1-inch lengths to achieve bulk density of about 0.11-0.13 kg/L (7-8 lb/ft^3). Bagasse is pneumatically conveyed to a cyclone which feeds the propane-fired rotary drum dryer that reduces moisture content from an average of 43% to 15-20%. It is then fed pneumatically to a disengaging cyclone above the gasifier structure and conveyed to the gasifier feed system (Wiant, 1998).

The feed system consists of the day bin, weigh bin, lockhopper and lockhopper valves, metering bin, collector screw, and gasifier injector screw. The day bin holds about 40 minutes of prepared bagasse. It automatically refills the weigh bin to a selected batch weight. The two live-bottom screws in the weigh bin discharged the bagasse into the lockhopper. The lockhopper cycles bagasse from atmospheric to operating pressure. Nitrogen or propane is used to pressurize the lockhopper to above the operating pressure of gasifier to provide a positive pressure in the lockhopper. The bagasse was conveyed to the gasifier via a collector screw and injection screws (Wiant, 1998).

The design of the gasification system allowed about 90% of the gas flow to the hot gas cyclone and 10% to the HGCU system slipstream. The HGCU used ceramic candle filters for removal of entrained ash at 700 °C (1,292 °F) or less. Both product gas streams were delivered to the combustion flare at near atmospheric pressure.

Fluidized velocities were maintained to entrain ash with product gases. Recycling of carryover was not needed due to high carbon conversion. The non-entrained inerts are periodically discharged from the reactor bottom. Some test results comparing to the 12 ton/day PDU at GTI are shown in Table 12.

Table 12. Test Results of Renugas® Gasifier (GTI)

Parameters	Demonstration Tests			PDU Test
	Oct. 95, no steam	Dec. 95, no steam	Dec. 95 with steam	1992 with steam
Temperature, °C (°F)	841 (1,545)	835 (1,535)	859 (1,575)	853 (1,568)
Pressure, kPa (psig)	296 (43)	421 (61)	503 (73)	2,137 (310)
Feed Rate, kg/h (lb/h)	1,048 (2,310)	1,714 (3,779)	1,561 (3,441)	254 (560)
Moisture of Bagasse, %	26	31	17	18
	Dry inert-free gas composition (% by volume)			
Hydrogen	12.0	12.1	18.4	18.1
Carbon monoxide	27.0	29.1	26.2	26.1
Carbon dioxide	49.9	45.6	39.0	37.6
Methane	9.0	10.4	14.9	17.3
C_2 species	1.4	1.9	1.5	0.5
C_3 species	0.8	0.7	--	0.3
HHV, MJ/m3 (Btu/ft^3)	9.95 (267)	10.9 (292)	11.4 (307)	12.6 (338)
Carbon Conversion, %	95	96	98	96

The tests from the demonstration plant were performed at lower pressure than the PDU. The heating value of the fuel gas is lower than the results from the PDU.

Stable operation of the hot-gas cleanup was achieved at 704 °C (1,300 °F), 172-862 kPa (25-125 psi), 2-40 min pulse cycles, and 318-499 kg/h (700-1,100 lb/h). There was no evidence of ash penetration and ash bridging. In addition, no filter candles were broken during operation. The oils and tars contained very small quantities of reactive components that were susceptible to cracking and carbon deposition on the filter surface. They did not affect filter operation, and they could be completely consumed in gas turbine combustors.

The Renugas® gasification plant demonstrated continuous operation with bagasse and integrated operation of the gasifier and HGCU. The major problem in the operation was the low-bulk density of the bagasse which led to difficulty in feeder operation. Furthermore, the residual sugars in the bagasse dust interrupted the lockhopper operation. The demonstration in Hawaii has been discontinued due to lack of funds.

1.1.2.3.2 Renugas® Pilot Plant in Tampere, Finland

The Renugas® technology was licensed to Tampella Power of Finland in 1989. A 27.2 metric ton/day (30-ton/day) plant based on coal and 90.7 metric ton/day (100 ton/day) plant based on biomass were built and commissioned in 1993 by Tampella's subsidiary, Enviropower, in Tampere, Finland, to further the development for IGCC applications. The gasification demonstration plant in Tampere, Finland, was designed for a maximum pressure of 2,413 kPa (350 psi) and a maximum temperature of 982 °C (1,800 °F). It was originally designed for coal at 27.2 metric ton/day (30 ton/day), but can also handle biomass at 90.7 metric ton/day (100 ton/day). The plant was designed to evaluate the HGCU and clean fuel gas production for IGCC applications. It was integrated with an onsite co-generation plant. In 1997, Carbona, Inc. was formed as a result of the restructuring of Enviropower, and it maintains the exclusive license of the Renugas® technology from GTI for development in Europe, Canada, Brazil, and South Africa. The license for the development in the Pacific Rim and Pacific Basin was awarded to PICHTR. The demonstration plant is now owned and operated by Carbona, Inc. It now serves as a test facility, and it will not operate in the summer from June to September because heat is not needed by the city district heating system. The flow diagram of the demonstration plant is shown in Figure 27.

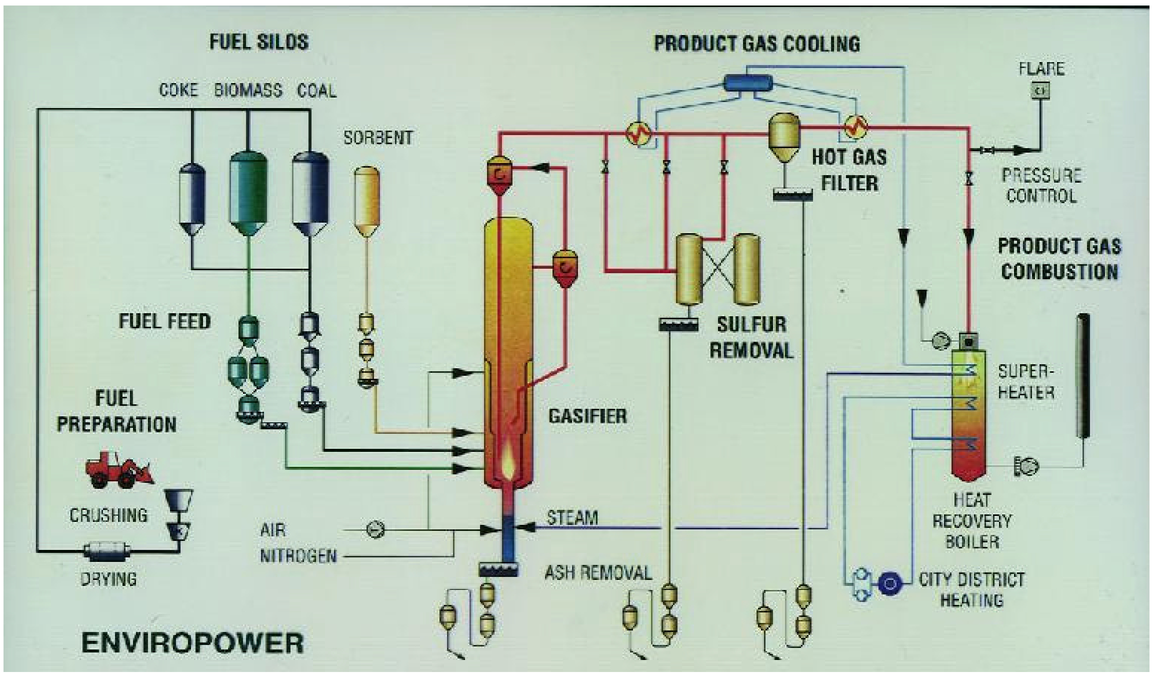

Figure 27. Coal/Biomass Demonstration Plant at Tampere, Finland (Courtesy of Carbona)

The plant has separate coal and biomass feed systems. Sulfur removal is needed only for coal gasification. The sorbent was developed in collaboration with Research Triangle Park (RTI) in the U.S. Figure 28 is the schematic diagram of the gasification system. The operating conditions of the demonstration plant are shown in Table 13.

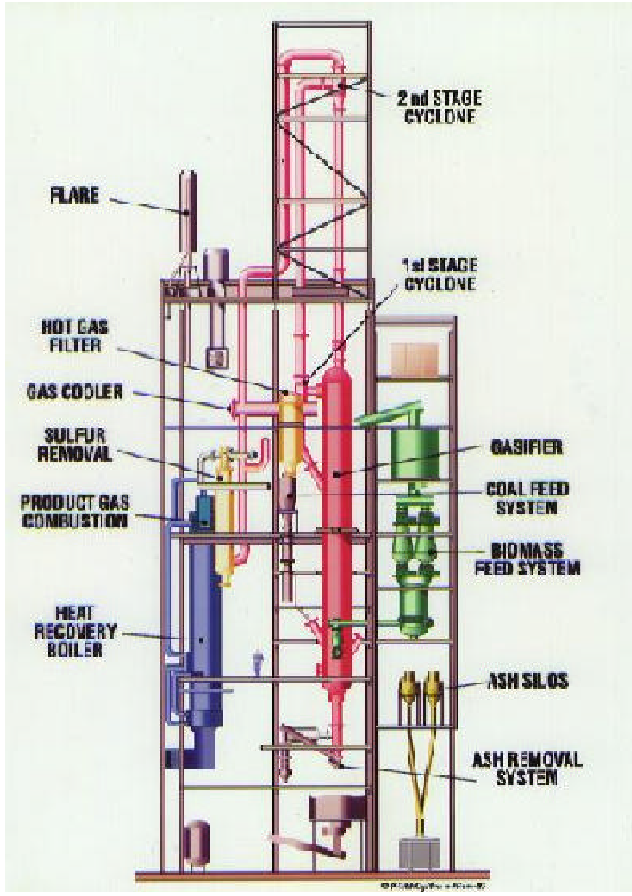

Figure 28. Gasification Demonstration Plant at Tampere, Finland (Courtesy of Carbona)

Table 13. Operating Conditions of the Demonstration Gasification Plant in Tampere

Parameter	Condition	
Pressure	7-22 bar(g)	100-325 psig
Temperature	700-950 °C	1,290-1,740 °F
Feed Rate	0.38-1.12 kg/s	3,016-9,186 lb/h
Thermal Input	5.0-17.0 MJ/s	17.1-58.2 MMBtu/h
Air Feed Rate	0.60-1.63 kg/s	4,762-12,940 lb/h
Steam Feed Rate	0.04-0.26 kg/s	320-2,090 lb/h
Superficial Gas Velocity	0.5-1.2 m/s	1.6-3.9 ft/s
Filter Temperature	450-570 °C	840-1,060 °F

The various feedstocks and their quantity tested at the GASPI plant are shown in Table 14. All of these fuels were tested under air-blown conditions. The composition of the gas produced from the GASPI plant using wood waste is shown in Table 15.

Table 14. Feedstock Tested at Demonstration Plant in Tampere

Fuel	Quantity, metric ton (ton)
Wood Chips	1,630 (1,797)
Forest Residue	1,750 (1,929)
Paper Mill Waste (bark, paper, sludge)	1,180 (1,300)
Willow	400 (441)
Straw with coal	20 (+ 120 metric ton of coal) (22 + 132)
Alfalfa	300 (331)

Table 15. Composition of Gas Produced from Demonstration Plant in Tampere

Gas Component	Concentration (vol. %)
CO	18.7
H_2	14.5
CH_4	4.2
CO_2	11.0
H_2O	10.0
N_2	41.6
C_xH_y (light tars), ppmv	<6,000
Heavy tars, ppmv	<100
NH_3, HCN, ppmv	400-2,000
H_2S, COS, ppmv	<100
Alkalines (Na+K),ppmv	<0.1
HCl, ppmv	<10
Dust, ppmv	<5
LHV, kJ/Nm3 (Btu/scf)	5,530 (138)

A picture of the demonstration plant is shown in Figure 29. The tall building in the middle houses the gasification system with the 2nd stage cyclone located on top of the building. The building is about 36.6 m (120 ft) tall with the cyclone extended another 9.1 m (30 ft) into the atmosphere. The structure to the right hand side of the building is the fuel preparation and storage area. The building behind the gasification building houses the heat generation system. The detached building to the left of the plant consists of the office facility. The air, nitrogen, and propane (for startup) tanks are located near the front of the picture.

Figure 29. Picture of the Gasification Demonstration Plant in Tampere, Finalnd (Courtesy of Carbona)

1.1.2.3.3 Renugas® VEGA IGCC Demonstration Project

Vattenfall AB started the evaluation of the VEGA IGCC project in Sweden in 1989. The IGCC plant generated 60 MW_e and 65 MW_{th} with 140 MW fuel input using the Tampella process (Renugas®). The overall efficiency of the plant was estimated to be above 40% (Lindman, 1993). Air- blown gasification was selected because of the significant investment in the air separation unit. The location of the IGCC plant was in the city of Eskilstuna, Sweden. The demonstration was planned for 1996. A flow diagram of the biomass IGCC is shown in Figure 30.

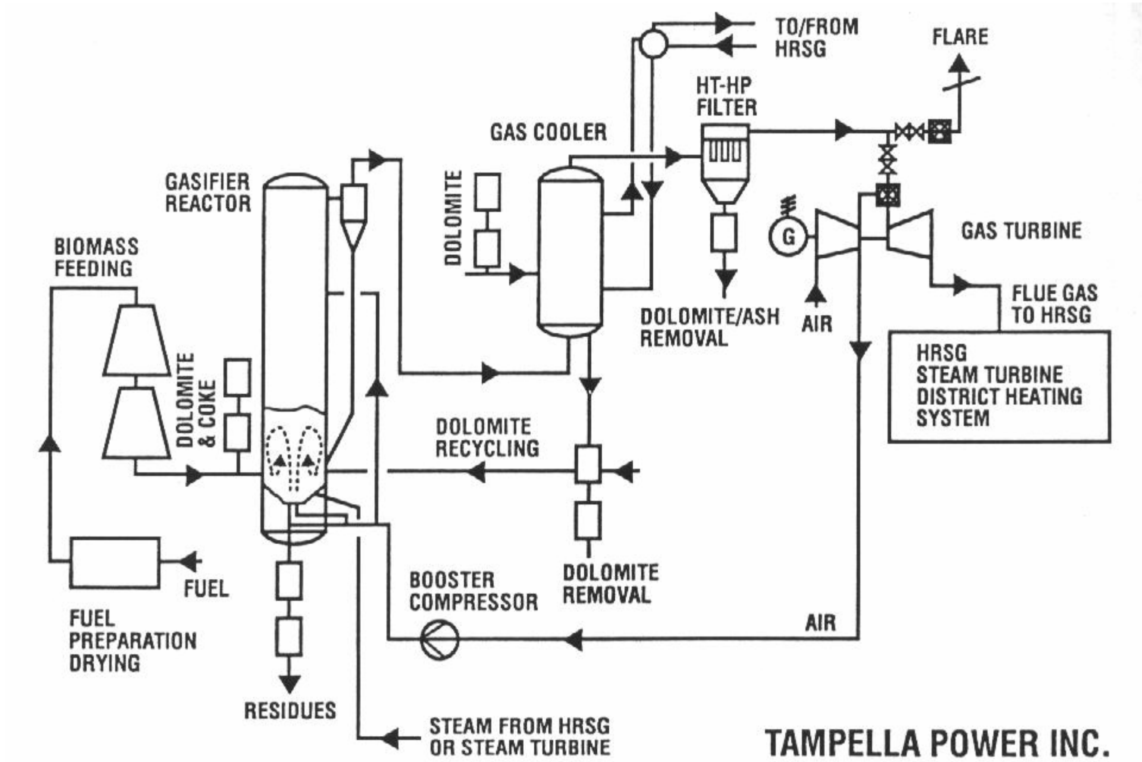

Figure 30. Flow Diagram of the Proposed VEGA Biomass IGCC in Sweden (Lindman, 1993)

1.1.2.3.4 Biocycle Project in Denmark

This is the second BIGCC project funded by the European Commission. It was originally foreseen to be carried out in Denmark. However, it was transferred to Finland in the city of Kotka because of economic reasons and the restructuring of Enviropower to Carbona Oy. The gasification technology was originally developed at the GTI in the U.S. and further refined in a 15-20 MW_{th} pilot plant in Finland by Enviropower. The plant will generate 7.0 MW_e (net) at 8.2 MJ/s (7,772 Btu/s) of heat with net overall efficiency of 87.1%. A process flow sheet is shown in Figure 31. The biofuel at about 50% moisture is crushed or chipped and dried to 15-20% moisture with steam extracted from the steam turbine and evaporated condensate. The compressed air for gasification is extracted from the gas turbine compressor operating at 1,100-1,400 kPa (160-203 psi). The gasification takes place at 850-950 °C (1,562-1,742 °F) and 2,200 kPa (319 psi). The hot-gas clean-up is based on ceramic filters after initial cooling to 350-550 °C (662-1,022 °F). The gas is fed to the combustion chamber of the gas turbine. The heat recovery steam generator is equipped with a single pressure steam system including economizer, evaporator and superheater. The latest information indicates that this project has been canceled.

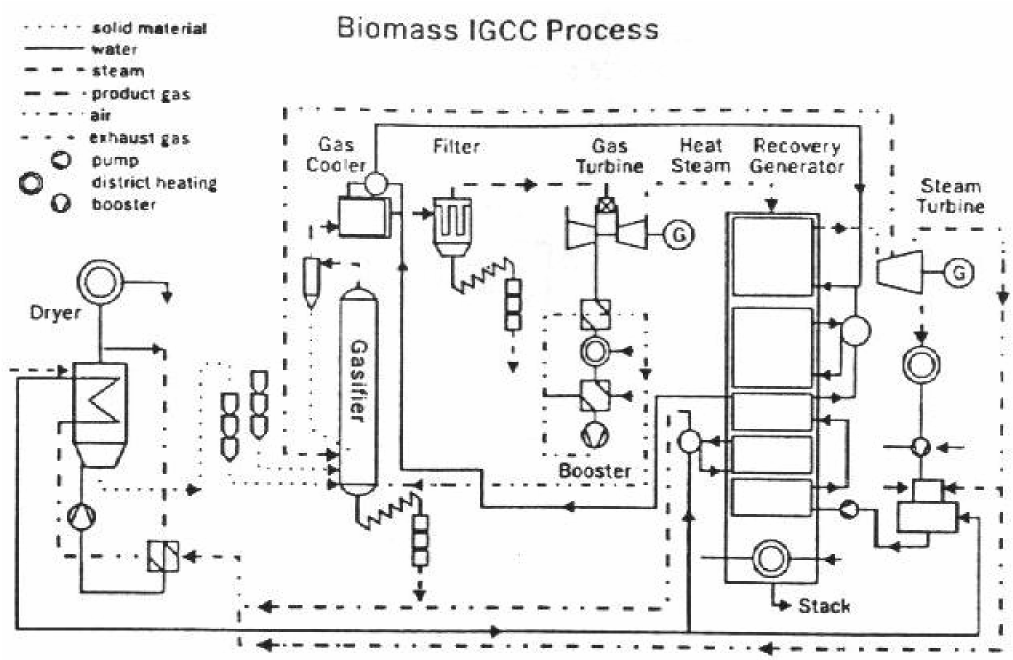

Figure 31. Biocycle Project in Finland

1.1.2.3.5 Renugas® MnVAP IGCC Demonstration Project

In 1998, the Renugas® technology was selected for a proposed IGCC project by the Minnesota Valley Alfalfa Produces (MnVAP) in Granite Falls, Minnesota, to provide 75-103 MW_e. The estimated cost of the project was about $1,643/kW. The IGCC plant would consume 997.9 metric ton/day (1,100 ton/day) of alfalfa stem for power production. Extensive testing of the alfalfa was performed at Carbona's pilot plant in Finland. DOE announced that it would no longer participate in the cooperative agreement with MnVAP project and decided not to fund the construction of the power plant and the associated processing facilities (Federal Register: September 20, 1999).

1.1.2.4 Energy Farm Project in Di Cascina, Italy

A project on biomass-based IGCC was planned for Di Cascina, Italy (Beenackers, 1997 and www.bioeletttrica.it). This project was one of three BIGCC demonstration projects funded by the European Commission within the framework of the THERMIE Programme. The joint-stock company, BIOELETTRICA S.p.A. will implement the project. The shareholders of the company are USF Smogless S.p.A., EDP-Electricidade de Portugal S.A., Energia Verde S.p.A., Lurgi Umwelt GmbH, and Fumagalli S.p.A. They were awarded for the supply of the main systems for the plant in May 1997. The plant design and testing are underway and is expected to enter into commercial operation in 2001.

This project will demonstrate the technical and economic feasibility of power-generation from biomass using the IGCC concept. The gasification system features the Lurgi atmospheric air-blown circulating fluidized-bed gasifier integrated with a 11.9 MW_e, single-shaft, heavy-duty gas turbine, suited to burn the low-calorific value syngas produced by the gasifier. The gasifier is supplied from Lurgi, and the turbine is from Nuovo Pignone. A heat-recovery steam-generator will provide steam to a 5 MW_e condensing steam turbine. The plant's net thermal efficiency is about 33 %. A process flow sheet is shown in Figure 32.

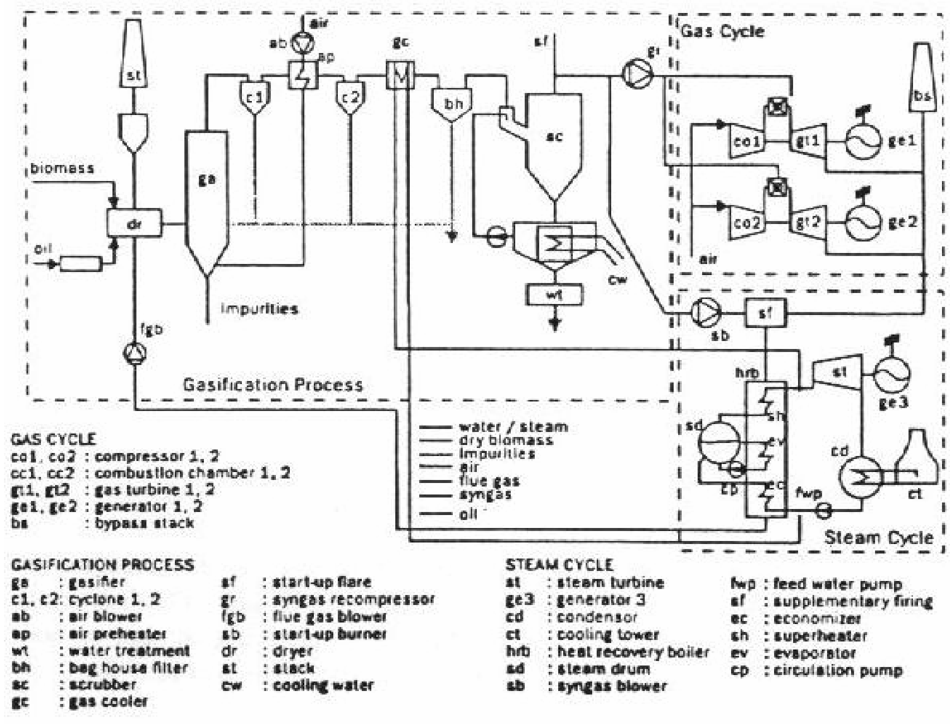

Figure 32. Flow Diagram of the Energy Farm Project in Italy

The fuel will consist not only of short rotation forestry (SRF), but also of forestry and agricultural residues. The wood species will include poplar, robinia, willow, and chestnut, whereas the agricultural residues will comprise olive stones and grape-seed flour.

In this process, wet wood will be shredded to chips (30x30x6 mm or 1.18x1.18x0236 inch) before mixing with the agricultural residues. Flue gases from the heat-recovery steam-generator (HRSG) are used to dry the biofuel to the desired moisture content (8-10%). The dried fuel is gasified in the CFB gasifier supplied by Lurgi to produce the syngas. The gasification takes place at about 800 °C (1,470 °F) and 140 kPa. This syngas is cooled in two stages during which syngas is cooled from 800 to 600 °C (1,472-1,112 °F) while the gasification air is preheated to 500 °C (932 °F). The syngas is cooled in the second stage to 240 °C (464 °F) in the waste heat boiler for steam production. The char and particulates are removed by passing syngas through a cyclone and a bag filter. The syngas is washed in a wet-scrubber and cooled to 45 °C (113 °F). Then it is compressed in several inter-cooled stages and delivered to a PGT10 B/1 gas turbine.

It was found that this project has faced difficulties because of the change of supplier for the gasification technology (Henk de Lange at Bioelettrica, personal communication). The problem seems to have been resolved. The new supplier of the gasification technology has not been identified, however. Public information will be announced around September 2001 according to Giuseppe Neri at Bioelettrica (personal communication).

1.1.2.5 ARBRE Energy Project

The third BIGCC project funded by the European Commission was the ARBRE project (ARable Biomass Renewable Energy) to be located at the 2,000 MW_e Eggborough Power station in the Aire Valley, North Yorkshire of UK. This project will provide a net electrical output of 8 MW_e with an efficiency of 30.6%. The process flow sheet is shown in Figure 33 (www.arbre.co.uk).

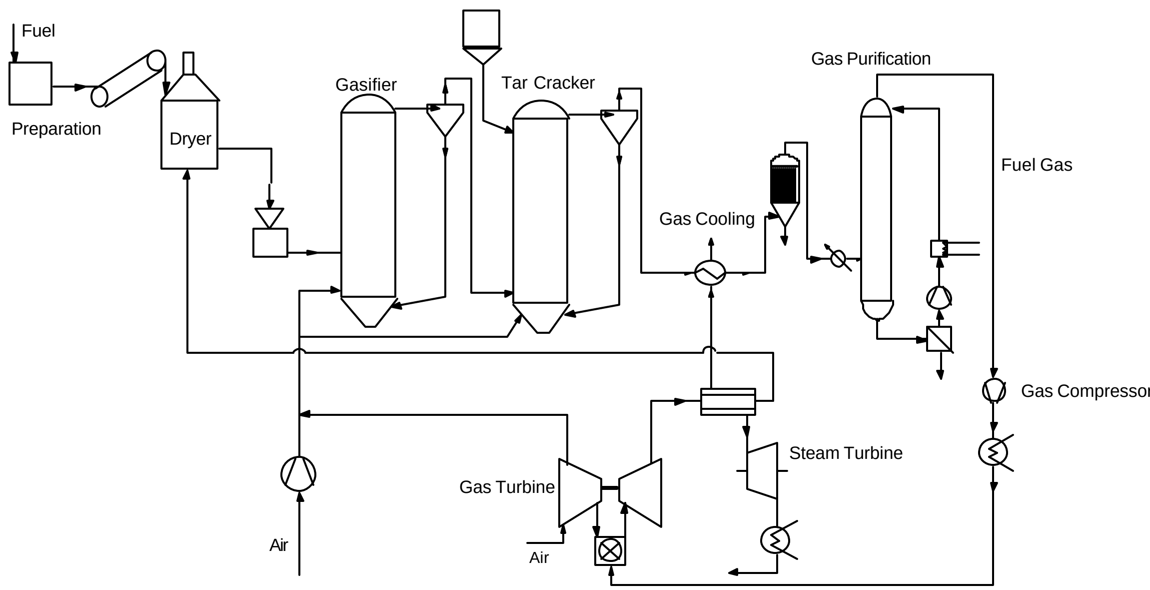

Figure 33. ARBRE Project in Yorkshire, UK

The biofuel for this project contains about 80% short rotation forestry based on 2,600 ha (6,424.6 acres) of a mixture of willow and hybrid poplar. The coppice will be used throughout the year with onsite covered storage. The feedstock is dried to 10-20% moisture by the low-grade heat from the system. It is expected that the drying will take up to 2 days to complete. The gasification technology is supplied by TPS. The details of the TPS gasification system can be found in the TPS section. The plant was partially completed by the end of 1999. A picture of the plant is shown in Figure 34 and a picture of the gasification section is shown in Figure 35 (Morris, 2000).

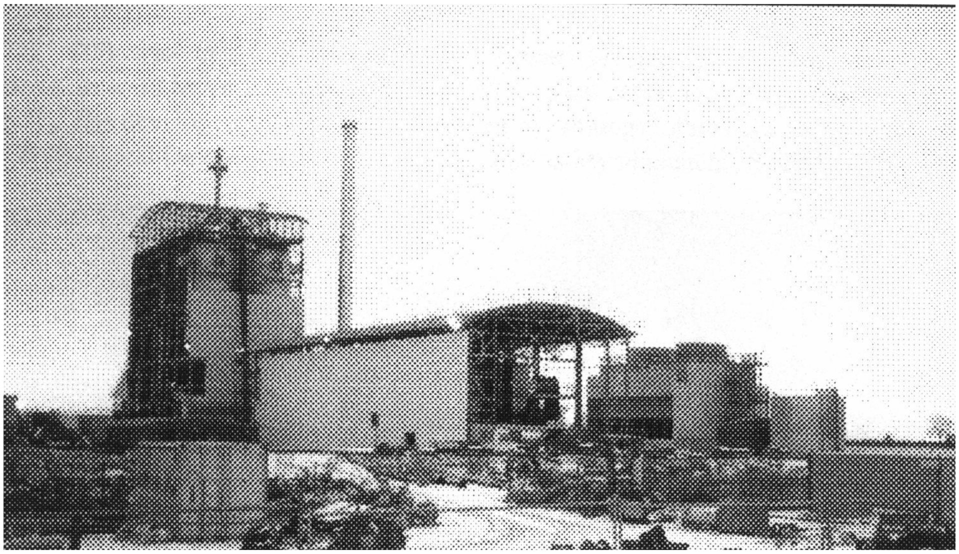

Figure 34. Project ARBRE site at Yorkshire, UK as of December, 1999

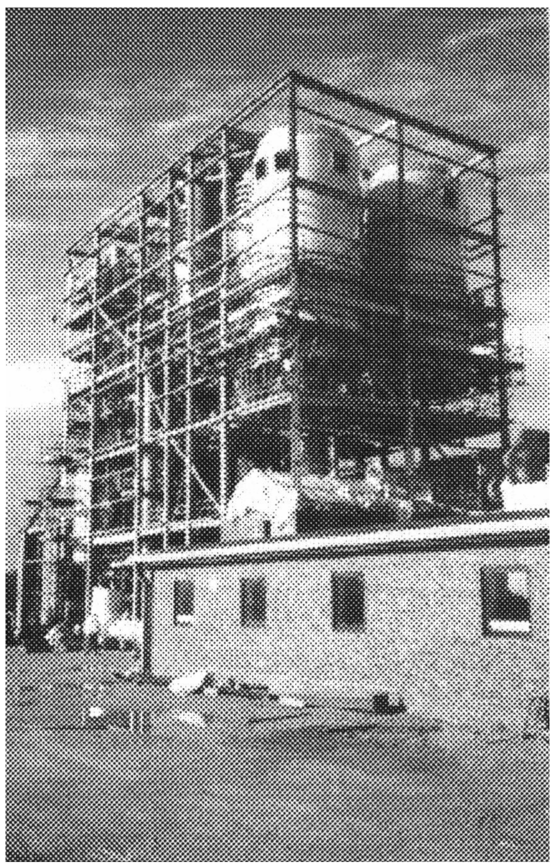

Figure 35. Gasification Section of Project ARBRE Plant

The construction of the BIGCC plant should have been completed by now and should be undergoing startup testing.

1.1.2.6 Brazil Biomass Integration Gasification-Gas Turbine

A Biomass Integration Gasification-Gas Turbine (BIG-GT) project was proposed by Eletrobrás (Brazilian Electric Power Co.) and CHESF (Companhia Hidro Electrica do São Francisco) in April 1991. This involved building a 30 MW_e BIG-GT in the state of Bahia, Brazil, using wood or sugar cane bagasse as fuel. The project was named SIGAME (Wood Gasification Integrated System for Electricity Generation). This was intended to confirm the technical and commercial viability of producing electricity from biomass using the integrated gasification combined cycle system. It was originally predicted that the commercial operation would begin in 2001.

Global Environment Facility (GEF) and the World Bank considered funding the pilot demonstration project because of its potential for efficient and fuel-flexible use of biomass for power production. The GEF was formed in 1990 and is administered by the World Bank. Its task is to fund environmental conservation projects, mainly in the Third World. The project was initialized in 1993. The short-term objective of the BIG-GT project is to establish a globally-replicable prototype unit on a commercial scale for the cogeneration of electricity based on the gasification of wood chips or sugarcane bagasse. The long-term objective of this project is to reduce global warming by lowering CO_2 emissions from fossil fuels.

Two gasification systems in combination with the General Electric LM-2500 aeroderivative gas turbine were chosen for final evaluation. The first technology was from TPS Termiska Processor AB. It was an atmospheric fluidized-bed gasifier where the product gas is cleaned with cold quench wet scrubbing. The second gasification technology was the pressurized fluidized-bed reactor offered from Bioflow (now Foster Wheeler). Hot-gas clean-up with ceramic filters were used in this system. TPS has finished all the gasification testing with bagasse in their gasifier in late 1994. The gasification testing by Bioflow at the Värnamo plant in Sweden was uncertain at that time. Phase I of the project resulted in the selection of the TPS system. Phase II of the project involved the World Bank contracting with EPRI to perform an economic and risk evaluation of the Brazil BIG-GT project based on EPRI's model ("BIOPOWER: Biomass and Waste Fuel Power Plant Performance and Cost Model," EPRI TR-101774, March 1985). An economic study using the two gasification technologies for the BIG-GT in Brazil was finished and published ("BIOPOWER: Biomass and Waste Fuel Power Plant Performance and Cost Model, Version 1.01," EPRI TR-101774, Rev. March 1996).

The proposed BIG-GT demonstration plant will produce about 40 MW_e and deliver about 32 MW of electricity to the grid. The wood will be chipped and dried onsite with waste heat from the system and then gasified inside the atmospheric fluidized-bed gasifier. The syngas is subjected to a series of conditioning steps for removal of tars, ammonia, and fine particulates. The BIG-GT is expected to have a high heating valve (HHV) of 38.0 % and net heat rate of 9473 kJ/kWh (8982 Btu/kWh) on a HHV basis. The consumption of biomass fuel will be 115,562 dry metric ton/a (127,385 ton/a).

EPRI used their BIOPOWER spreadsheet model for sensitivity analyses to determine the parameters most critical in determining the economics and risks associated with the BIG-

GT project. It was found that the most critical parameters are total plant cost, discount rate, and availability/capacity factor. The funding of the demonstration project by the World Bank would contribute significantly to Brazil's capability to deploy biomass gasification power plants in Brazil after year 2010 and would reduce the delivered cost of electricity from the plants.

This project was postponed and scheduled for 2000 (Juniper Consultancy Services Ltd, 2000). However, it was found on the World Bank website that the project was dropped (June, 2001). Hence, the future of this BIG-GT is not clear.

1.1.2.7 BioCoComb Project

Biofuel for Co-Combustion (BioCoComb) is a project where syngas produced from biomass is co-combusted in a pulverized coal-fired power station. The project was supported by a European Community Thermie Fund and has been installed by Austrian Energy and Environment in Zeltweg, Austria. The power plant has a capacity of 137 MW of electricity from coal. The gasifier is capable of gasifying biomass such as bark, wood chips, and sawdust, and has a thermal capacity of 10 MW_{th}. The produced gas replaces about 3% of the coal fired in the boiler (Anderl, 1999).

The major advantages of the BioCoComb concept are:
1. low gas quality sufficient for co-firing,
2. no hot-gas cleaning or cooling,
3. no predrying or milling of the biomass,
4. relatively low temperatures in the gasifier to prevent slagging,
5. favorable effects on power plant emissions (CO_2, NO_x),
6. no severe modifications of the existing coal-fired boiler,
7. high flexibility in arranging and integrating the main components into existing plants, and
8. reduction of ammonia water consumption from the re-burning in the coal boiler.

In this process, the biomass is converted to low calorific value (LCV) syngas in a separate gasification reactor. The syngas is fed to a conventional coal boiler where it is burned with the coal. This concept offers the highest flexibility in integrating the main components into the existing plants.

The Zeltweg power plant has been operated since 1962. Lignite was initially used as fuel, but was switched to hard coal 20 years later. Main steam data (HP/reheat) are 185 bar/44 bar (2,683/638 psi) at 535 °C (995 °F). The flue gas cleaning systems were renewed. NO_x removal is achieved by a selective non-catalytic reactor (SNCR) system with ammonia injection, and SO_2 removal is performed in a CFB-desulphurization reactor.

In the external circulating fluidized-bed gasifier, the biomass is combusted in a sub-stoichiometric atmosphere through an auto-thermal method. Predrying or milling of the biomass is not necessary. The size of the biomass is limited to 30x30x100 mm (1.18x1.18x3.94 inch). Low calorific value (LCV) gas is produced from incomplete combustion due to the lack of oxygen. The gasification temperature is maintained at about 800-850 °C (1,472-1,562 °F) which is below the critical ash melting points. Mechanical attrition inside the gasifier produces very fine char particles. The larger particles are separated by cyclones and recycled back to the gasifier. The fine particles leave the gasifier and are combusted in the furnace of the power plant. Hot gas or cool gas cleaning is not necessary with this system. Re-burning of the produced gas occurs in the boiler when the unburned hydrocarbons are cracked to create radicals which attack the NO_x and decompose it to nitrogen and oxygen again. This was known only with natural gas in the past. A schematic diagram showing the gasification system is shown in Figure 36.

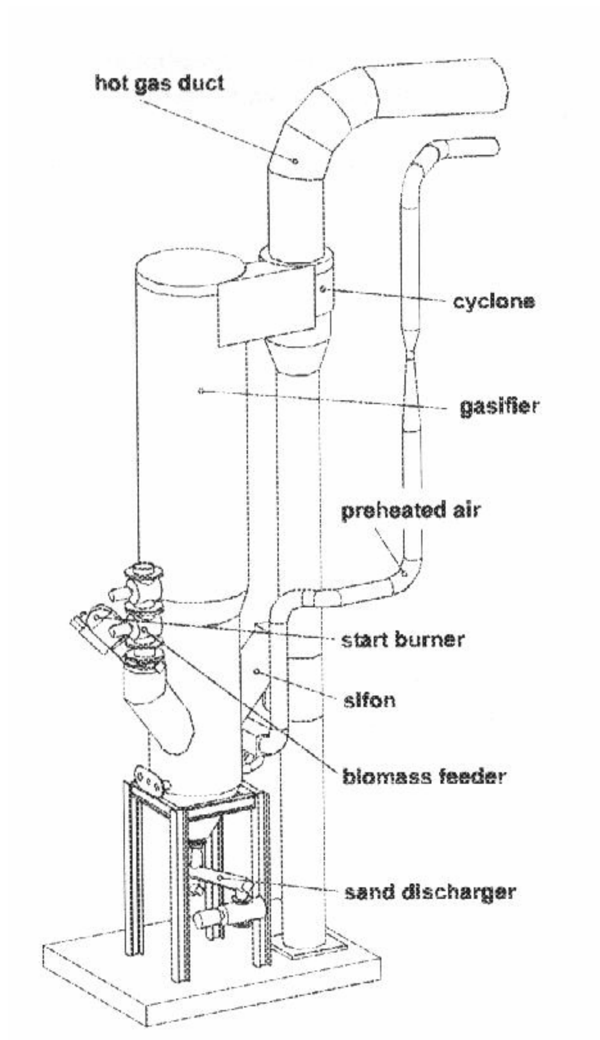

Figure 36. CFB Gasifie r Used at the BioCoComb Project in Austria

The CFB gasifier is constructed using steel with a brick and concrete refractory lining. The gasification chamber is a vertical tube without internal mechanical components or heat exchangers. Compressed air is injected into the gasifier via an open nozzle grid located at the bottom of the gasifier. The air is taken from the recuperator of the coal boiler at about 270 °C (518 °F). The bed material is a fine sand of a defined particle fraction. A startup burner is employed to heat up the reactor and for emergencies. The reaction temperature and bed behavior are the main parameters controlled by varying the air flow. A water-cooled screw conveyor is located at the bottom of the gasifier to allow discharge of bed material and incombustible parts. The ash is expected to be very fine and will leave the gasifier with the gas.

The BioCoComb concept was started in 1993, and the detailed planning phase began September 1996. Construction began in May 1997 with commissioning taking place in November. First gasification was achieved on December 10, 1997. More than 1,905 metric tons (2,100 tons) of biomass was gasified during the first two months of operation. The main fuel was spruce bark with a moisture content of approximately 50-55% (open storage). Chopped wood and sawdust from larch trees were also used. The operation of the gasifier was very successful with complete biomass conversion. The discharge bed material contained less than 0.4% of carbon. Homogenous temperatures were recorded throughout the gasifier. The power range of the gasifier was varied between 5 and 13 MW_{th}. The quality of the product was similar to that expected, and its composition is shown in Table 16.

Table 16. Calculated Gas Composition at 55% Moisture

Component	Mole %
O_2	0.00
N_2	38.44
CO	4.55
CO_2	12.31
CH_4	0.00
H_2	10.54
H_2O	34.15
Lower Heating Value, MJ/kg df (Btu/lb)	1.61 (692)

The combustion of the produced gas in the boiler worked without problems. The reburning effects in the boiler reduced the ammonia water consumption by 10-15%. There was no detectable damage to the gasifier after inspection. There was no deposition of tars in the system, especially in the hot-gas duct. The furnace walls of the boiler did not show more slagging than usual. The problems associated with the biomass feed system such as bridging in the dosing silo, slipping of frozen biomass on inclined belts, or blocking on the rotating disc separator were more or less all solved. The first demonstration of this concept is at the Lahti gasification plant in Finland.

1.1.2.8 Summary of Advanced Biomass Gasification Systems

Of the seven biomass integrated gasification combined cycle projects, the Bioflow gasification plant in Värnamo has proven that converting the biomass to heat and power is feasible. The Energy Farm project in Italy is undergoing some changes and will proceed in the near future. The other two demonstrations that are operating are the

ARBRE plant in U.K. and the Burlington plant in the U.S. The proposed BIGCC demonstration projects are summarized in Table 17.

Table 17. Advanced Gasification Demonstration (adapted from Beenackers, 1997)

PROJECT TITLE	BIOFLOW	FERCO SilvaGas®	Hawaii I
LOCATION	Värnamo, Sweden	Burlington, Vermont, USA	Paia, Hawaii,
CONSORTIUM	Ahlstrom, Fi; Sydkraft, and Foster Wheeler from Sweden	FERCO, Battelle, Burlington Electric, and ZURN NEPCO, all of USA	HICHTR, Sta HC&S, Ralpl GTI, NREL,
STATUS	The plant was shutdown in Oct. 1999*	In Operation - discontinuous	Terminated
TECHNOLOGY			
Gasification Process	IGCC	Gasification/Gas Turbine	IGCC/Metha
Gasifier	Press. CFB	Atm. Indirectly Heated	Press. FB
Gasifier Supplier	Ahlstrom (Bioflow)	Battelle	GTI (RENUC
Tar Removal	Hot gas cleanup	Cataltytic – DN-34	Hot gas clean
Operating Conditions, °C/bar(g) (°F/psi)	950-1000/22 (1472-1832/319)	650-760/1.01 (1202-1400/14.6)	835/5 (1535/7
Gas Cleaning	Ceramic filter	wet scrubber	Ceramic filter
Gas Turbine	EGT/Typhoon	not specified	
Steam Turbine	Nadrowski	not specified	
CAPACITY			
Installed Capacity, MW_e/MW_{th}	6/9	15	3-5
Net Electric Output, MW_e	6	NA	5.0
Net Heat Output, MW_{th}	9	NA	NA
Thermal Efficiency, %		36 (estimated)	up to 80%
Electric Efficiency, %	32	32 (net), 34.5 (gross) (estimated)	30-35 (estima
Overall Efficiency, %	83	80 (estimated)	NA
Heating value of syngas, MJ/Nm^3 (Btu/scf)	5.3-6.3 (153-182)	15.5-17.3 (450-500)	10 (289)
FEEDSTOCK			
Source	Wood waste	Wood	Bagasse
Feedstock requirement, metric ton/day (ton/day) (MW)	90.7 (100) (18)	181[1] (200[1]), 318[2] (350[2])	90.7 (100)

* Biomass Technology Group (www.btgworld.com); NA – not available; 1 – design throughput; 2 – actual throughput

Table 17. Advanced Gasification Demonstration (Cont'd)

PROJECT TITLE	BIOCYCLE	SIGAME/BIG-GT	Energy Farm
LOCATION	Relocated to Finland	Bahia, Brazil	Di Cascina, Italy
CONSORTIUM	ELSAM, ELKRAFT, and VEAG from Denmark, and TRACTEBEL, BE	Electrobrás, CHESF, and Shell from Brazil	ENEL, LURGI, LE RENE ,IT; SWP and EGT of UK, and EDP, PO
STATUS	Terminated	Not funded	Change of Gasification Technol
TECHNOLOGY			
ification Process	IGCC	IGCC	IGCC
ifier	Press. CFB	Atm. CFB	Atm. CFB
ifier Supplier	Carbona	TPS	Lurgi (original supplier)
Removal	Dolomite – Hot gas cleanup	Catalytic – Dolomite	Water Scrubbing
rating Conditions, °C/bar (°F/psi)	850-950/22 (1562-1742/319)	850-900/1.5 (1562-1652/21.8)	800/1.4 (1472/20.3)
Cleaning	Ceramic filter	Bag filter/scrubbing	Bag Filter
Turbine	EGT/Typhoon	GE LM2500	EGT/Typhoon
m Turbine			
CAPACITY			
alled Capacity, MW_e/MW_{th}	7.9	40	14.3
Electric Output, MW_e	7.2	32	11.9
Heat Output, MW_{th}	6.78	NA	0
tric Efficiency, %	39.9	41	33
rall Efficiency, %	77.3	NA	NA
FEEDSTOCK			
rce	Wood – SRC/Forest	*Eucalyptus* plantation	Wood – SRC/Forest
dstock requirement, metric ton/day /day)	76 (84)	463 (510)	134 (148)