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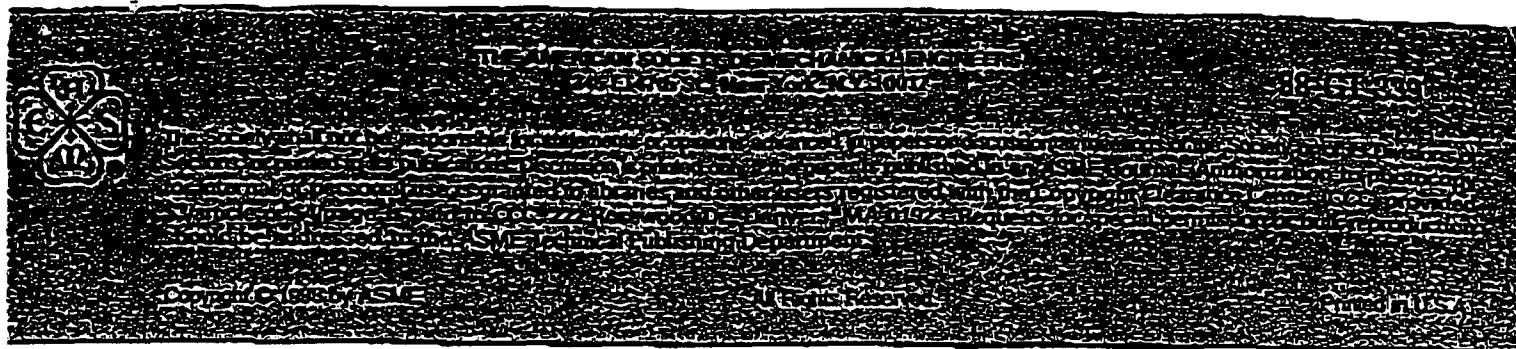07/26/99   11:08   ☎202 463 2423   AF&PA   ☒001/009

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COMBINED BIOMASS AND BLACK LIQUOR GASIFIER/GAS TURBINE COGENERATION AT PULP AND PAPER MILLS

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ABSTRACT

Kraft pulp and paper mills generate large quantities of black liquor and byproduct biomass suitable for gasification. These fuels are used today for onsite cogeneration of heat and power in boiler/steam turbine systems. Gasification technologies under development would enable these fuels to be used in gas turbines. This paper reports results of detailed full-load performance modeling of pulp-mill cogeneration systems based on gasifier/gas turbine technologies and, for comparison, on conventional steam-turbine cogeneration technologies. Pressurized, oxygen-blown black liquor gasification, the most advanced of proposed commercial black liquor gasifier designs, is considered, together with three alternative biomass gasifier designs under commercial development (high-pressure air-blown, low-pressure air-blown, and low-pressure indirectly-heated). Heavy-duty industrial gas turbines of the 70-MW$_e$ and 25-MW$_e$ class are included in the analysis. Results indicate that gasification-based cogeneration with biomass-derived fuels would transform a typical pulp mill into a significant power exporter and would also offer possibilities for net reductions in emissions of carbon dioxide relative to present practice.

INTRODUCTION

As discussed elsewhere (Consonni, et al. 1998; Larson and Raymond, 1997a), the kraft pulp and paper industry in North America is faced with the need to retire much of its black liquor and biomass-fueled steam turbine cogeneration capacity during the next 5 to 20 years. This presents a unique economic opportunity to introduce gas turbine-based cogeneration systems. The biomass and black liquor gasification technologies needed to enable the use of gas turbines are under active development by companies around the world and are likely to be commercially available within the paper industry's time frame for retiring existing systems (Larson and Raymond, 1997b). Long-term economics appear favorable for gasifier/gas turbine technology using black liquor (Larson et al., 1998) or biomass (Weyerhaeuser et al., 1995).

This paper presents results of performance modeling of integrated black liquor- and biomass-gasifier/gas turbine-combined cycle cogeneration systems for pulp and paper mills. Cogeneration systems at such mills are designed firstly to meet process steam demands and recover pulping chemicals from black liquor, the lignin-rich byproduct from the wood digestion stage in kraft pulping. Black liquor is burned today in Tomlinson recovery boilers to generate steam and an inorganic smelt from which pulping chemicals are reconstituted. A variety of fuels, including bark, other biomass residues, and fossil fuels, are used as supplemental fuels at kraft pulp mills today, because the black liquor by itself is typically insufficient to provide all process steam requirements. For simplicity, here we consider the use of only black liquor and byproduct biomass as cogeneration fuels at a kraft mill.

Consonni, et al. (1998), modeled the performance of three alternative black liquor gasifier/gas turbine cogeneration technologies and considered the use of a biomass boiler to generate additional steam when steam derived from black liquor was insufficient. The present work extends the analysis of Consonni, et al., by considering gasification of the biomass rather than combustion. Three biomass gasifier designs are considered. Since the focus of the present work is on biomass, only the black liquor gasifier closest to commercial readiness (pressurized, oxygen-blown) is considered. The black liquor gasifier is coupled with a 70-MW$_e$ class gas turbine. The biomass gasifiers are coupled with 25-MW$_e$ or 70-MW$_e$ class turbines. Heat recovery steam generators (HRSGs) use exhaust heat from each turbine to raise steam that is delivered to a common steam turbine (Fig. 1, lower). The black liquor flow rate is set to meet the fuel-gas demands of the 70-MW$_e$ class turbine, and is thus constant regardless of the design of the biomass portion of the plant. A minimum biomass fuel rate is established by the fuel demands of the biomass-coupled turbine. Higher biomass rates are considered to allow for supplementary firing of the biomass-coupled turbine's HRSG when greater amounts of process steam are needed than can be provided by the gas turbine exhaust alone (see Fig. 1, lower). Results from a parallel analysis with a Tomlinson recovery boiler substituted for the black liquor gasifier/gas turbine/HRSG system is also included (Fig. 1, upper).

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Tomlinson black liquor boiler with biomass-gasifier/gas turbine combined cycle
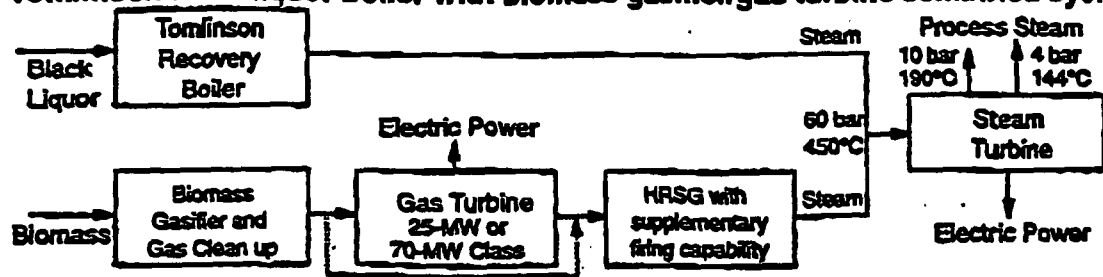
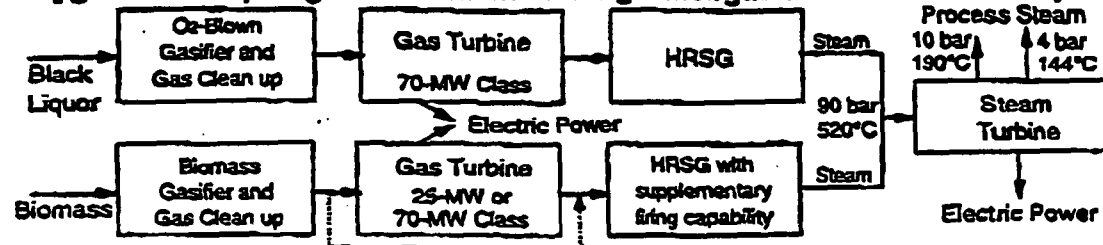# Oxygen black liquor gasifier with biomass gasifier/gas turbine combined cycle

Fig. 1. Block representation of cogeneration systems modeled.

CALCULATING PERFORMANCE

The approach used to calculate cogeneration performance follows that described by Consonni, et al. (1998), who also describe details of the modeling of the two black liquor conversion systems considered here (oxygen gasifier and Tomlinson furnace). The discussion of methodology here is restricted to key issues relating specifically to modeling the use of biomass in gasifier/gas turbine systems.

Biomass Gasification

A variety of relatively large scale biomass gasification technologies are at various advanced stages of development (Weyerhaeuser, et al., 1995; Williams and Larson, 1996; Larson and Raymond, 1997b). Three gasifier/gas cleanup designs are considered here: (i) atmospheric-pressure air-blown fluidized-bed gasification with wet scrubbing, e.g. the technology under development by TPS (Waldheim and Carpentieri, 1998), (ii) pressurized air-blown fluidized-bed gasification with hot-gas cleanup, e.g. the technology under development by Carbona (Salo et al., 1998), and (iii) atmospheric-pressure indirectly-heated gasification with wet scrubbing, specifically the Battelle Columbus Laboratory (BCL) technology licensed for North American applications to FERCO (Paisley and Anson, 1997).

The assumed biomass gasifier feedstock in the modeling here is a mixture of pulpwood harvesting and thinning residuals and sawmill waste, with an initial moisture content of 50%. The waste bark and hog fuel generated at a typical kraft pulp mill converting logs into pulp amounts to some 0.25 dry tonnes of biomass per air-dry tonne of pulp product (0.25 t_b/t_p). Many mills may have access to much more biomass. One detailed study around a Weyerhaeuser pulp mill in North Carolina identified a sustainable supply of up to 3 t_b/t_p at reasonable cost in the form of harvest residues and self- and externally-generated mill residuals (Weyerhaeuser et al., 1995).

Table 1 gives the detailed biomass composition (in the table caption), as well as modeled performance of alternative gasifiers. (The overall model includes drying of the biomass from 50% to 20% moisture

content before gasification.) Empirical gasifier performance estimates given by Weyerhaeuser, et al. (1995) have been used as a guide for the expected performance of the air-blown gasifier designs, supplemented by discussions with developers of these designs (specifically TPS and Carbona). BCL technology developers have been consulted in arriving at the performance results for the third design. The gasifier heat/mass balances in Table 1 reflect reasonable values of gasification temperatures, carbon conversions, cold-gas efficiencies, heat losses, and product gas heating values. Gas compositions have been allowed to vary somewhat from published values in order to close the heat/mass balances, because small changes in gas composition alone have relatively little impact on calculated overall cycle performance (Hughes and Larson, 1998). For additional discussion of the three biomass gasifier designs considered here, see Weyerhaeuser,

Table 1. Modeled performance of alternative biomass gasifiers. The feedstock in all cases is biomass with 20% moisture content with the following composition (dry mass basis): 50.2% carbon, 5.4% hydrogen, 34.4% oxygen, 0.2% nitrogen, and 4% ash. Its higher heating value is 20.47 MJ/dry kg.

	Low-Pressure Indirect-Heat	Low-Pressure Air-blown	High-Pressure Air-blown
Gasifier T, °C	865	920	850
Gasifier P, bar	1.90	1.34	19.8
Gasifier inputs			
Air, wt dry biomass	0.0	1.48	1.80
Air temperature, °C	—	266	343
Steam, wt dry biomass	0.0	0.0	0.014
Recycled gas, wt dry bio.	0.06	0.0	0.0
Heat loss, % biomass BHV	2.9	1.21	0.97
Carbon conv. to gas, %	70.1	96.9	97.4
Cold gas efficiency, % HHV	72.4	79.0	82.8
Clean gas to turbine			
Mass, wt dry biomass	0.82	2.44	3.09
HHV, MJ/kg	18.1	6.47	5.48
Volume % Ar	0.0	0.468	0.433
CH_4	13.049	3.575	0.052
CO	39.236	21.533	24.394
CO_2	13.083	12.480	3.245
H_2	29.428	16.599	15.504
H_2O	0.432	4.826	15.504
C_2H_4	4.316	1.238	0.502
C_2H_6	0.259	0.126	0.0
N_2	0.182	39.248	38.366
NH_3	0.0	0.307	0.0

(a) Steam conditions are 26.9 bar, 441°C.

(b) Carbon in fuel gas divided by carbon into gasifier. The value for the indirectly heated gasifier appears abnormally low because, unlike the air-blown designs, char is oxidized in a separate vessel from that which generates the fuel gas. Thus, the carbon from the char is not reflected in the carbon conversion figure for the indirectly-heated gasifier.

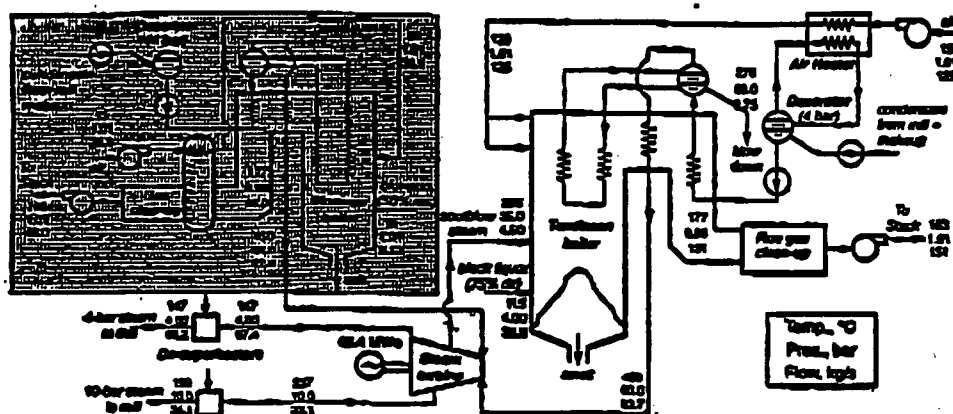(c) For cases without supplemental firing (see Fig. 1 for further clarification).

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Fig. 2. Heat/mass balance for Tomlinson black liquor boiler with supplemental biomass boiler. (shaded area) when delivering16.3 GJ/tp process steam. Adapted from Consonni, et al., (1998).

et al. (1995); Craig and Mann (1996); Consonni and Larson (1996); Larson and Raymond (1997b).

Turbomachinery Assumptions

The accurate modeling of actual commercial gas turbines is an important feature of the process modeling software used. Turbines with the characteristics of the Siemens KWU 64.3a and the ABB GT-10 are simulated here to represent state-of-the-art 70-MW$_e$ class and 25-MW$_e$ class industrial turbines. These two power output classes were selected because the requisite fuel delivery falls within the range of black liquor or biomass fuel that is, or could be made, available at many pulp mills in North America. A 70-MW$_e$ class machine is integrated with the black liquor gasifier (Fig. 1, lower). A comparable black liquor flow is specified for the cases involving the Tomlinson boiler. Because it is expected that atmospheric-pressure biomass gasification systems, particularly air-blown designs, will be more competitive at smaller scale than pressurized systems (Larson and Raymond, 1997a), the atmospheric-pressure gasifiers are coupled with the smaller of the two turbines. The atmospheric-pressure indirectly heated gasifier is also modeled with the larger turbine, as is the pressurized air-blown gasifier.

A single steam turbine is used in all cases, with steam being generated from heat sources derived from both black liquor and biomass (Fig. 1). A range of total process steam demand is considered. Either a single-extraction, back-pressure or a double-extraction condensing turbine is used depending on the level of process steam required.[1] (The back-pressure turbine is the paper-industry standard today.) Process steam is delivered at 10 bar and 4 bar in a mass ratio of 1:2.

Plant Integration

To reduce the complexity of the required modeling, heat integration within the biomass sub-section of a full plant has been done independently of that within the black liquor processing sub-section. Figures 2 and 3 (adapted from Consonni *et al.* (1998)] show illustrative heat and mass balances (for a particular

process steam demand) for the two black liquor processing systems considered. A supplemental biomass boiler included in the mass balances is shown in the shaded areas of these figures. For the simulations reported in this paper, these shaded sections were, in essence, replaced by alternative biomass-gasifier/gas turbine-HRSG systems. For each of the three biomass gasifiers considered here, Figs. 4-6 show illustrative heat and mass balances for the biomass sub-sections for a particular level of process steam demand. Steam delivered from the black liquor sub-section is indicated in these figures. This steam is combined with the steam generated in the biomass sub-section and the combined flow is delivered to the steam turbine.

Within each sub-section, efforts have been made to optimize the heat integration among components to maximize efficiency within practical cost (and material) constraints. Heat exchanger networks have been designed following two guidelines. First, high-temperature gas streams transfer heat only to water or steam-water mixtures (evaporators); the high heat transfer coefficients guarantee acceptable heat exchanger metal temperatures. Second, to the extent possible in practice, heat is transferred across relatively small temperature differences and between flows having similar thermal capacities, which reduces irreversibilities.

RESULTS AND DISCUSSION
Overall Performance

Overall calculated performance is summarized in Figure 7, which shows power output per metric tonne of pulp product (kWh/t$_p$) for different levels of process steam production (GJ/t$_p$) for each of the technology configurations simulated (upper set of curves) and the
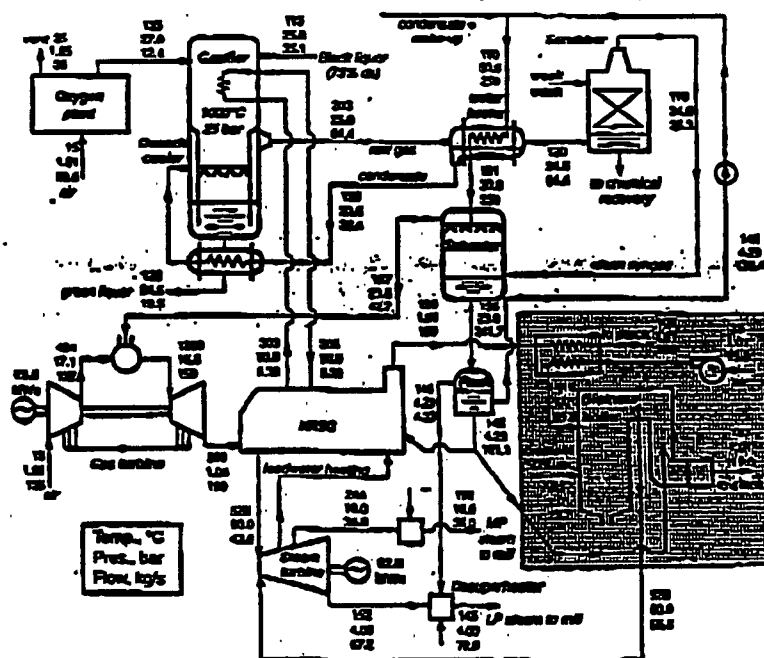

Fig. 3. Heat/mass balance for oxygen-blown black liquor gasifier/gas turbine with supplemental biomass boiler (shaded area) when delivering16.3 GJ/tp process steam. Adapted from Consonni, et al., (1998).

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[1] The performance estimates in this paper are for new cogeneration systems. In some practical situations, it may be feasible to continue to use an existing steam turbine by making minor modifications to it (e.g., increasing steam admission area) while replacing only the steam generating systems at a mill. In such cases, performance would be different from results in this paper.

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Fig. 4. Heat/mass balance for biomass-gasifier/gas turbine portion of a full cogeneration system that includes a Tomlinson black liquor boiler (see Fig. 1). The biomass gasifier is a low-pressure air-blown design and is fueling a 25-MWₑ class turbine. The complete system delivers 16.3 GJ/tp of process steam.
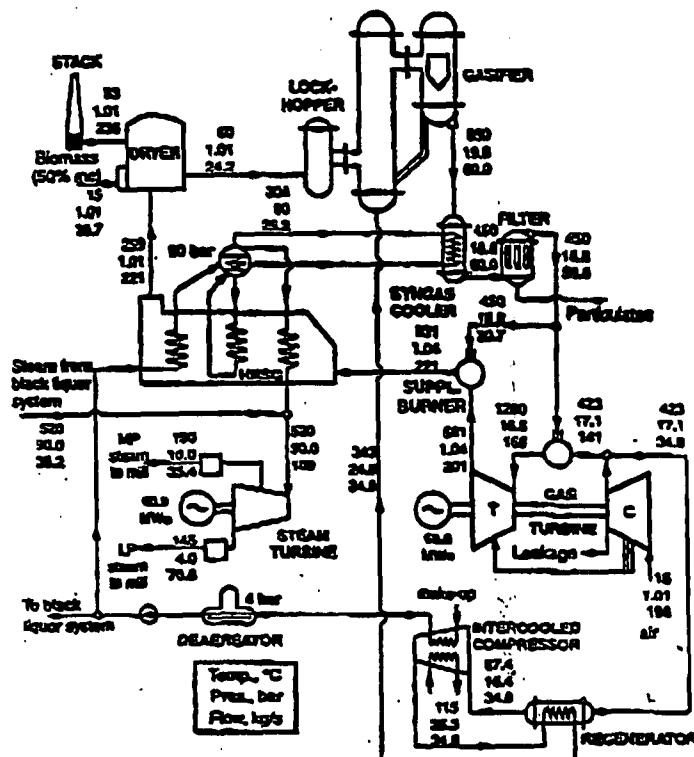

Fig. 5. Heat/mass balance for biomass-gasifier/gas turbine portion of a full cogeneration system that includes a black liquor gasifier/gas turbine (see Fig. 2). The biomass gasifier is a high-pressure air-blown design and is fueling a 70-MWₑ class turbine. The complete system delivers 16.3 GJ/tp of process steam.

Fig. 6. Heat/mass balance for biomass-gasifier/gas turbine portion of a full cogeneration system that includes a black liquor gasifier (see Fig. 2). The biomass gasifier is a low-pressure indirectly-heated design and is fueling a 25-MWₑ class turbine. The complete system delivers 16.3 GJ/tp of process steam.
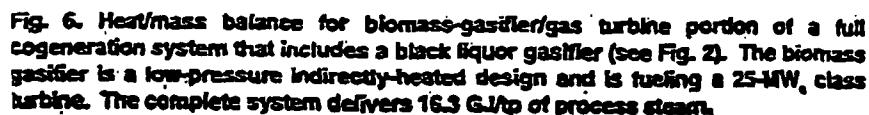
corresponding biomass fuel requirements per tonne of pulp (t_b/t_p) (lower set of curves).

For reference, Fig. 7 includes results from Consonni et al. (1998) for the two cases when biomass is burned in a boiler rather than being gasified. In these cases, process steam is delivered through a back-pressure turbine, so power output increases with increasing process steam demand. For the cases involving gasification of biomass, the minimum power output point represents the maximum process steam delivery possible without supplemental firing of the gas turbine HRSG. For any one of these systems, process steam demand levels to the right of the minimum power point require greater biomass consumption to enable supplemental firing of the HRSG. Process steam is delivered through a back-pressure turbine in these cases. The right end point represents the situation in which there is just sufficient oxygen in the exhaust of the biomass-coupled turbine to enable complete combustion of the amount of supplemental fuel required to generate the particular process steam demand. (This curve could extend further to the right, e.g. by introducing additional fresh combustion air, but this is not considered here.) To the left of the minimum power point, no supplemental firing is required. Biomass consumption remains constant (to meet the fuel demands of the gas turbine), and lower process steam demands enable a condensing turbine to be used to generate additional power. The left end-point represents the case when all of the steam generated in the biomass portion of the plant
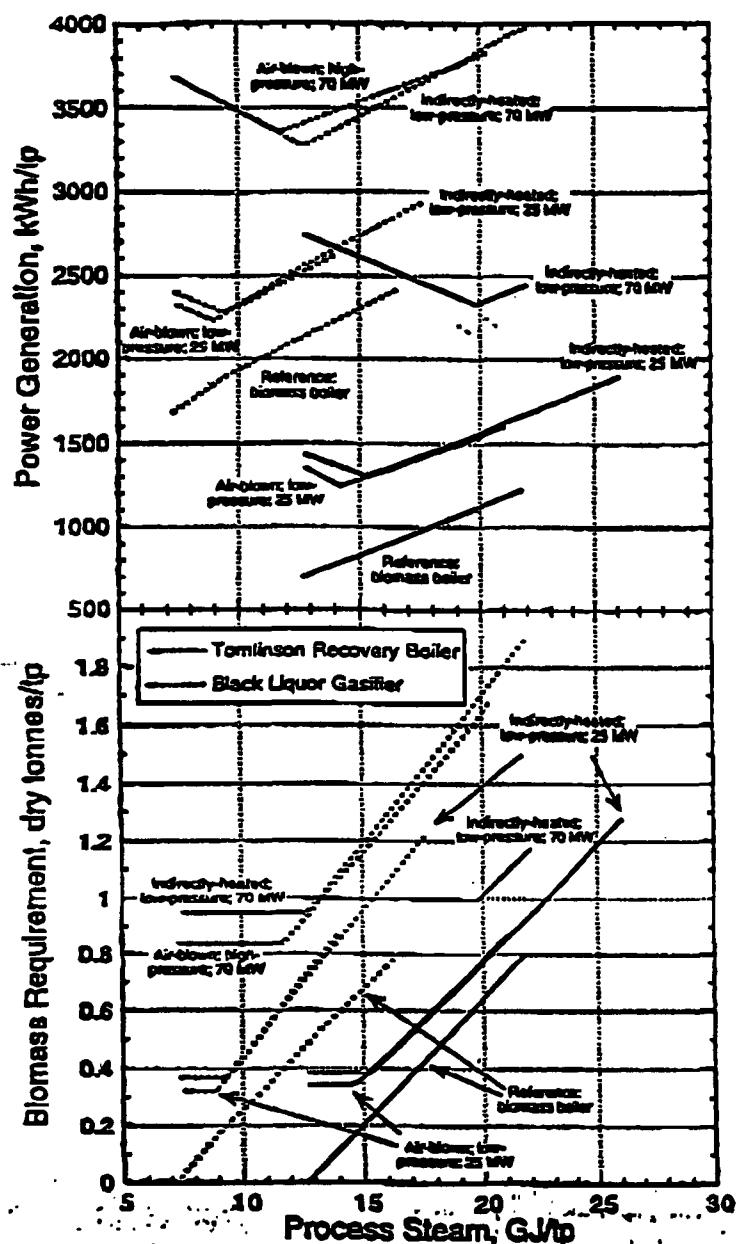
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Fig. 7. Electric power generation and biomass fuel consumption for all cogeneration systems considered in this paper. In all cases, the black liquor consumption is 25 GJ/t. The two "reference" cases are from Consonni et al. (1998).

electrical power. With the 70-MW$_e$ class turbine, much more power is generated than in the reference (biomass boiler) case. The additional biomass required to accomplish this varies considerably with the level of process steam demand.

The results for the cases involving the black liquor gasifier (dashed lines in Fig. 7) parallel those for the set of Tomlinson cases. Power production is considerably higher, however, due to the more efficient conversion of black liquor to electricity. Biomass consumption is also higher in large part because in these cases steam delivered from the black liquor processing section of the plant is lower than with Tomlinson black liquor processing. The performance for one additional biomass gasifier is also included: the high-pressure air-blown design with a 70-MW$_e$ class turbine. This case produces a comparable amount of power as the indirectly-heated gasifier coupled to a 70-MW$_e$ class turbine, but consumes less biomass for a given process steam demand, reflecting the higher efficiency of the pressurized gasification system.

Mill-Specific Performance Comparisons

Comparisons among alternative plant configurations are illuminated by a mill-specific examination. For concreteness, process steam and power demands representative of a typical present-day U.S. mill are considered—16.3 GJ/t$_p$ and 656 kWh/t$_p$ (net of the cogeneration plant). [Consonni, et al. (1998) give process energy demand data that helps put these figures in international perspective.] Detailed heat and mass balances for plant configurations delivering 16.3 GJ/t$_p$ of process steam are shown in Fig. 2 and 3 for the reference cases involving biomass use in boilers. Figures 4-6 show heat and mass balances for the biomass sub-section for three of the configurations involving biomass gasification.

Table 2, which summarizes the performance of all systems, highlights the much greater power generation levels achievable with gasification. Biomass-gasifier/gas turbine systems coupled with a Tomlinson boiler (left half of Table 2) would produce 50% to 180% more power than the reference Tomlinson plus biomass boiler. When coupled with black liquor gasification (right half of Table 2), then power production is 230% to 320% more than the case using the Tomlinson and biomass boiler.

With one exception, the contribution of the steam cycle to total power production is approximately the same for all systems using a Tomlinson boiler (left half of Table 2) and for all systems using the black liquor gasifier (right half of Table 2), because process steam demand is fixed.[2] In the one case where this is not true (Tomlinson plus indirectly-heated gasifier with 70-MW$_e$ class turbine), the steam cycle involves a condensing steam turbine rather than a back-pressure turbine.

The last row in Table 2 bears on a situation in which the mill might be considering replacing an existing Tomlinson-based cogeneration system. A baseline alternative in this situation might be the installation of a new Tomlinson recovery boiler with a biomass boiler to augment steam delivery to a back-pressure steam turbine. If the mill has an opportunity to export power, then one of the other plant configurations in Table 2 might be adopted. Each generates more power than the baseline configuration, but each requires more biomass fuel as well. Dividing the incremental power generated by the incremental biomass consumed gives a measure of the marginal fuel cost associated with the increased power production. The high incremental efficiencies in Table 2 indicate that marginal fuel costs would be low. Investment and operating/maintenance costs would obviously also be considered in any full evaluation of alternative cogeneration options (Larson, et al. 1998).

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[2] Steam turbine power is higher for the cases involving black liquor gasification because of the higher steam generating pressure that can be used.

is condensed. (The curve could extend further to the left by condensing additional steam, but this is not considered here.)

Among the cases involving the Tomlinson boiler (solid lines in Fig. 7), the case when biomass is burned in a boiler provides the lowest power output for a given process steam demand. On the other hand, biomass fuel requirements are also lowest, because a boiler/steam turbine converts a larger fraction of input fuel to steam than does a biomass-gasifier/gas turbine-HRSG arrangement. However, the two gasifier systems using the 25-MW$_e$ class turbine (which have roughly comparable performance) consume relatively modest additional amounts of biomass (especially at larger process steam demand levels), while delivering considerably more

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Table 2. Summary comparison of alternative black liquor plus biomass cogeneration technologies for a pulp mill with a fixed process steam demand of 16.3 GJ/admt (GJ per air-dry metric tonne of pulp product). On a mass basis, half the process steam is delivered at 10-bar pressure and half at 4-bar. Fig. 2 shows a detailed flow sheet for one of the cases in this table.

Black Liquor system >	Tomlinson Recovery Boiler plus			O2 Black Liquor Gasifier, 70-MW class plus				
Biomass system >	Boiler[a]	Low-P air-blown gasifier	Indirectly-heated gasifier	Boiler[a]	Low-P air-blown gasifier	High-P air-blown gasifier	Indirectly heated gasifier	
MW class of biomass g.t >	—	25	25	70	—	25	70	25	70
Mill output, t/day		1248				1307			
Process steam, GJ/t		16.3				16.3			
Black liquor, t/d/t		1.74				1.74			
GJ/d/t, HHV		14.363				14.363			
GJ/t, HHV		25.0				25.0			
Biomass, t/t	0.318	0.469	0.45	0.997	0.783	—	1.277	1.108	1.315
GJ/t, HHV	20.00[b]	20.47	20.4	20.47	20.00[b]	—	20.47	20.47	20.47
GJ/t, HHV	6.36	9.60	9.15	20.41	15.66	—	26.14	22.27	26.92
% direct to steam[c]	100	27.3	16.0	0.0	100	(d)	34.6	66.5	28.0
Power generation, MWe									
Black liquor gas turbine	—	—	—	—	89.75	—	89.75	89.75	89.75
Biomass gas turbine	—	28.85	26.0	70.80	—	—	68.75	27.21	70.80
Steam cycle	48.4	48.99	48.8	70.90	62.00	—	60.88	61.19	60.89
Auxiliaries, MW	1.64	8.09	4.73	10.10	19.77	—	23.19	23.79	28.43
Net power generated									
MW	46.76	69.75	70.1	131.2	132.03	—	196.2	154.3	192.0
kWh/t	904	1349	1356	2537	2624	—	3603	2834	3543
Fraction total fuel HHV to:									
Electricity	0.104	0.140	0.14	0.201	0.215	—	0.254	0.216	0.246
Process steam	0.520	0.471	0.47	0.359	0.401	—	0.318	0.346	0.313
Electricity + steam	0.624	0.611	0.61	0.560	0.616	—	0.572	0.561	0.559
Power/steam ratio	0.20	0.30	0.30	0.56	0.54	—	0.80	0.62	0.78
Excess power available[e]									
MW	12.5	35.8	36.2	97.3	94.3	—	160.5	118.6	157.2
kWh/t	248	693	700	1881	1769	—	2947	2178	2887
Incremental Efficiency, % HHV[f]	—	49	54	42	59	—	49	44	46

(a) The results in this column are from Consonni, et al. (1996), where biomass with slightly different heating value and composition were used.
(b) Process steam is counted at 2.315 GJ/tonne for 10-bar steam and 2.276 GJ/tonne for 4-bar steam.
(c) This is the percentage of the biomass input that is used directly to raise steam for delivery to the steam turbine. It is 100% for the two biomass boiler cases. For the biomass gasifier cases, it corresponds to the percentage of the clean syngas production that is directed to supplementary firing of the HRSG.
(d) In this case, the amount of oxygen in the gas turbine exhaust flow is insufficient for complete combustion of the amount of supplementary-firing fuel that would be required to deliver a process steam demand of 16.3 GJ/t.
(e) This is power available in excess of the mill's assumed process requirements of 656 kWh/t.
(f) The numerator of the incremental efficiency is the amount of power produced (kWh) by a gasification-based system (any of the last 8 columns in the table) in excess of that consumed by the Tomlinson + biomass boiler system (column 1). The denominator is the HHV of the fuel consumed by the gasification-based system in excess of that consumed by the Tomlinson + biomass boiler system.

processing. The last two sets of bars are for cases with gasification of black liquor.

The first set of bars assumes fossil fuel (natural gas or coal) is used in a boiler to augment steam production from the Tomlinson furnace. All steam expands through a back-pressure turbine before being delivered to the process. The positive carbon emissions are due to the use of fossil fuel at the mill. The second set of bars assumes a biomass boiler is used in place of the fossil fuel boiler. Power production is the same as the first case, but carbon emissions are slightly negative now because carbon-neutral biomass has replaced the fossil fuels, and sale of some power to the grid eliminates a small amount of fossil-derived utility power. The third set of bars assumes a biomass gasifier/gas turbine (with supplementary firing of the HRSG) is used in place of the biomass boiler. The greater amount of power generated enables larger amounts of fossil-derived utility electricity to be eliminated, leading to larger negative carbon emissions. This trend is maintained in moving to the last two bars—greater and greater amounts of power are generated from carbon-neutral fuels, leading to more and more negative carbon emissions.

Greenhouse Gas Emissions Reductions

Assuming the black liquor and solid biomass energy resources at a pulp mill are derived from renewably produced wood, the use of these energy resources contributes little or no net emissions to the atmosphere of carbon dioxide, the most important of the greenhouse gases; CO_2 released in converting the feedstocks into power and heat is reabsorbed by new plant growth. To the extent that the use of these carbon-neutral resources can reduce the use of fossil fuels, net reductions in CO_2 emissions would result. The potential reductions in CO_2 emissions can be quantified using the above performance estimates. Consider a pulp mill with a production rate of 1300 t/day and process steam and power demands of 16.3 GJ/t and 656 kWh/t. (These are, approximately, the characteristics of the mill considered in Table 2.) For five powerhouse technology configurations, Fig. 8 shows the total power generated at the powerhouse while meeting process steam demand. Also shown for each case are two estimates of net annual carbon emissions from the mill. These emissions are calculated assuming that any power generated in excess of process needs is exported to a utility grid where it eliminates the need to generate an equivalent amount of power from natural gas or from coal (both cases are shown in Fig. 8). The first three sets of bars are for configurations involving a Tomlinson furnace for black liquor

CONCLUSIONS

The gas turbine-based cogeneration systems modeled here would permit kraft pulp and paper mills to produce far more power from self-generated renewable fuels than is the case today. In 1994, the U.S. pulp and paper industry produced some 48 million tonnes of kraft pulp (AFPA, 1995) and in the process consumed 1.15 EJ of black liquor and 0.4 EJ of biomass (AFPA, 1996). Assuming cogeneration facilities today generate 900 kWh/t, from these fuels, as modeled here (Table 2, left-hand column), total biomass-derived power generation in the kraft industry is some 43 billion kWh/year. The total paper industry (kraft and other products) burns fossil fuels to generate additional power and also purchases power.

On average, the present level of self-generated black liquor and biomass fuels would be sufficient to generate about 1350 kWh/t, or 450 kWh/t, in excess of present systems if used in cogeneration systems that include a Tomlinson boiler and a coupled biomass gasifier (e.g., see Table 2, second column, for which the ratio of black liquor-to-biomass energy is approximately 1.15/0.4). At a production level of 48 million t/year, kraft mills could produce an additional 22 billion kWh/year or nearly half of the 51 billion kWh that the total industry purchased in 1994 (AFPA, 1996).

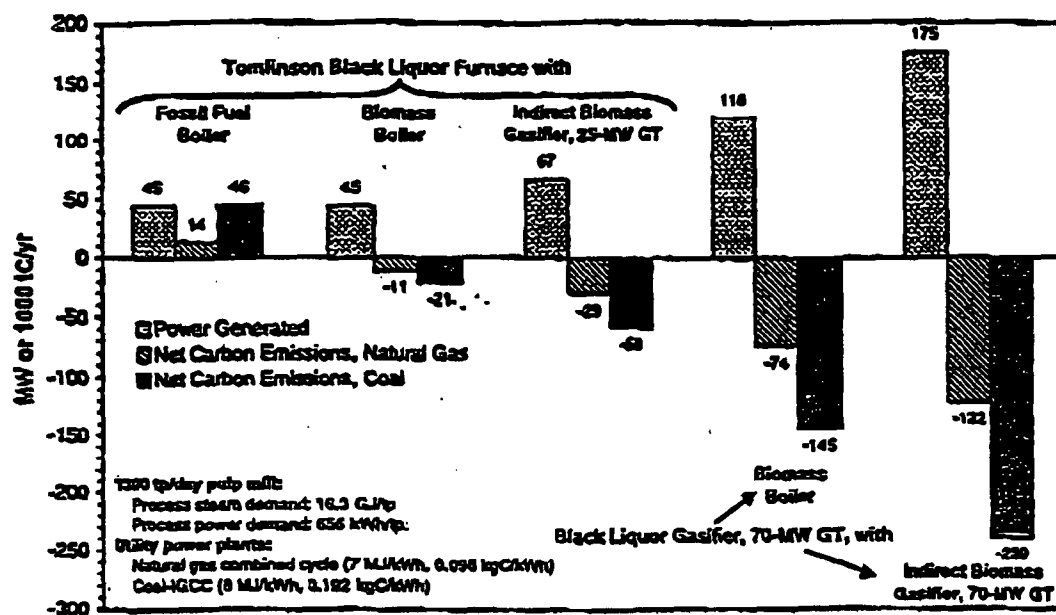Electricity generation at kraft mills would be increased even more

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Fig. 8. Power generation and net carbon emissions for five cogeneration plant configurations at a kraft pulp mill producing 1200 t/day. The carbon emission estimates assume that power generated at the mill in excess of that needed for pulp production would be sold and would eliminate an equivalent amount of power produced by a utility from fossil fuels (natural gas or coal).

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by the introduction of black liquor gasification. Because less process steam would be generated from the black liquor (compared to Tomlinson processing of the liquor), additional biomass residues would need to be used to meet steam demand. If the energy contribution of residues were raised to approximately that of the black liquor and both fuels were used in gasifier/gas turbine systems, total power generation might reach 3600 kWh/adtu (e.g. Table 2, third column from right), corresponding to 173 billion kWh at the 1994 kraft pulp production level (or over 20,000 MW of installed capacity). This would be some 130 billion kWh above the estimated present kraft industry electricity production from black liquor and biomass, and more than triple the amount of electricity purchased by the entire U.S. pulp and paper industry today. With the extra power coming from carbon-neutral biomass and eliminating fossil-derived electricity, total net emissions of carbon would fall by 13 million tonnes per year (displacing natural gas combined cycle power) to 25 million tonnes per year (displacing coal-gasifier/gas turbine combined cycle power). For comparison, carbon emissions from fossil fuel combustion in all U.S. industry in 1990 was 275 million tonnes (Watson *et al.*, 1996).

The economics of adopting gasifier-based cogeneration systems have not been discussed here, but they will be driven largely by the relative cost of purchased fuels and value of electricity sales and by relative capital investment requirements for competing systems. Preliminary cost studies, e.g. see Larson, *et al.* (1998) and Weyerhaeuser, *et al.* (1995), suggest that once gasification-based powerhouse technologies reach commercially-mature cost levels, they will compete well against boiler-based technologies.

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