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ENERGY ANALYSIS OF A KRAFT PULP MILL: POTENTIAL FOR ENERGY EFFICIENCY AND ADVANCED BIOMASS COGENERATION

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ABSTRACT

Energy use at a kraft pulp mill in the United States is analyzed in detail. Annual average process steam and electricity demands in the existing mill are 19.3 MMBtu per ADST and 687 kWh per ADST, respectively. This is relatively high by industry standards. The mill meets nearly all its electricity needs with a back-pressure steam turbine.

Higher electricity to heat ratios is an industry wide trend and anticipated at the mill. The potential for self-sufficiency in energy using only black liquor and bark available on-site is assessed based on the analysis of the present energy situation and potential process changes. The analysis here suggests that steam and electricity demand could be reduced by 8-9% by operating consistently at high production rates. Process modifications and retrofits using commercially proven technologies could reduce steam and electricity demand to as low as 9.7 MMBtu per ADST, a 50% reduction, and 556 kWh per ADST, a 19% reduction, respectively. Electricity demand could increase to about 640 kWh per ADST due to closed-cycle operation of the bleach plant and other efforts to improve environmental performance.

The retrofitted energy efficient mill with low environmental impact could be self-sufficient in steam and electricity using conventional technology, such as a back pressure steam turbine or a condensing extraction steam turbine. In addition to meeting mill energy demand, about 1,000 kWh per ADST would be available for export from the mill if gasification/combined cycle technology were used instead.

INTRODUCTION

In the United States, Scandinavia, and elsewhere, increasingly stringent environmental standards and regulations (12,18) are motivating pulp and paper mills to consider alternative process configurations and technologies. The energy impact of many ongoing and proposed process changes is a small increase in mill electricity use and a reduction in steam demand. This trend toward a ratio of higher electricity to heat use is expected to continue for the foreseeable future (24). The industry therefore has a long term interest in alternatives to the back pressure steam turbine cogeneration systems that are the existing industry standard. The potential for increasing efficiency and electricity to heat ratios with this technology is relatively limited.

Introducing advanced cogeneration technologies to meet the higher electricity to heat ratios also provides an economic opportunity for the industry. Historically, industry has had little incentive to produce electricity in excess of on-site needs. However, ongoing and planned reforms towards more competition in electricity markets in the United States and elsewhere can make it easier for pulp and paper mills to profit from selling electricity. Furthermore, the pulp and paper industry could play an important role in the development of biomass based renewable power generating energy technologies due to its direct access to low-cost wood waste and forestry residues.

Assessing the potential for future kraft mills to be energy self-sufficent (with excess energy as a potentially important by-product for export) requires

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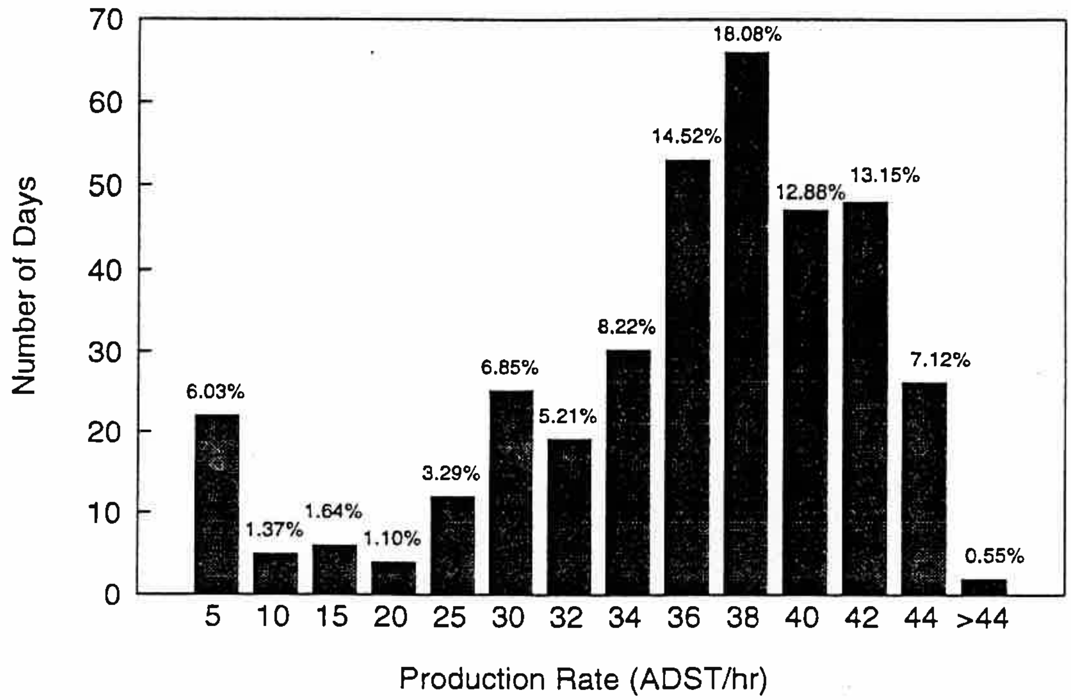

Figure 1. Production rate distribution for 1993 at the kraft pulp mill analyzed in this paper. The percentages indicate percent of total operational days for a given production rate range. Note that the mill operated at production rates of 34 ADST per hour and higher about 75% of the time.

a detailed understanding of how energy is used at present and how energy use may be changed in the future.

This paper presents a study of the energy use in a U.S. bleached kraft pulp mill. (Bleached and unbleached kraft pulp accounted for 82% of all pulp produced in the U.S. in 1993 (2).) An energy balance was constructed in an effort to understand energy consumption in major production processes at the mill and to estimate the potential for energy savings through better energy management and adoption of new technologies. The results of this analysis are used to study the impact that reduced energy-intensity of the mill would have on the choice of cogeneration technology for the mill. The cogeneration analysis considers conventional steam turbine cycles and black liquor and biomass integrated gasification/gas turbine combined cycles.

MILL DESCRIPTION

The mill produces an annual average of 790 air dry short tons (ADST) of bleached softwood market pulp per day. Batch digestion is followed by washing and screening and then oxygen delignification. Bleaching follows using hydrogen peroxide and chlorine dioxide. The pulp is then formed and dried to customer specifications before packaging. The weak black liquor is concentrated to approximately 70% solids content in a five-effect rising film evaporator and a 3-body concentrator.

During normal mill operation the recovery boiler burns about 1650 to 1750 tons per day of black liquor. Steam from the recovery boiler is expanded in a back-pressure turbine-generator with one extraction stage. A bark and oil fired boiler is used to generate additional steam to feed the turbine. The turbine meets about 95% of mill electricity demand. Reducing process steam use at the mill would reduce on-site electricity production and would lead to higher total purchased energy costs at present oil and electricity prices. Thus, the mill has little incentive to reduce steam use without changes to the cogeneration system.

The capacity of the recovery boiler to process black liquor limits the pulp production rate today, as in many other mills. The mill is now evaluating options to expand chemicals recovery capacity and reduce purchased oil.

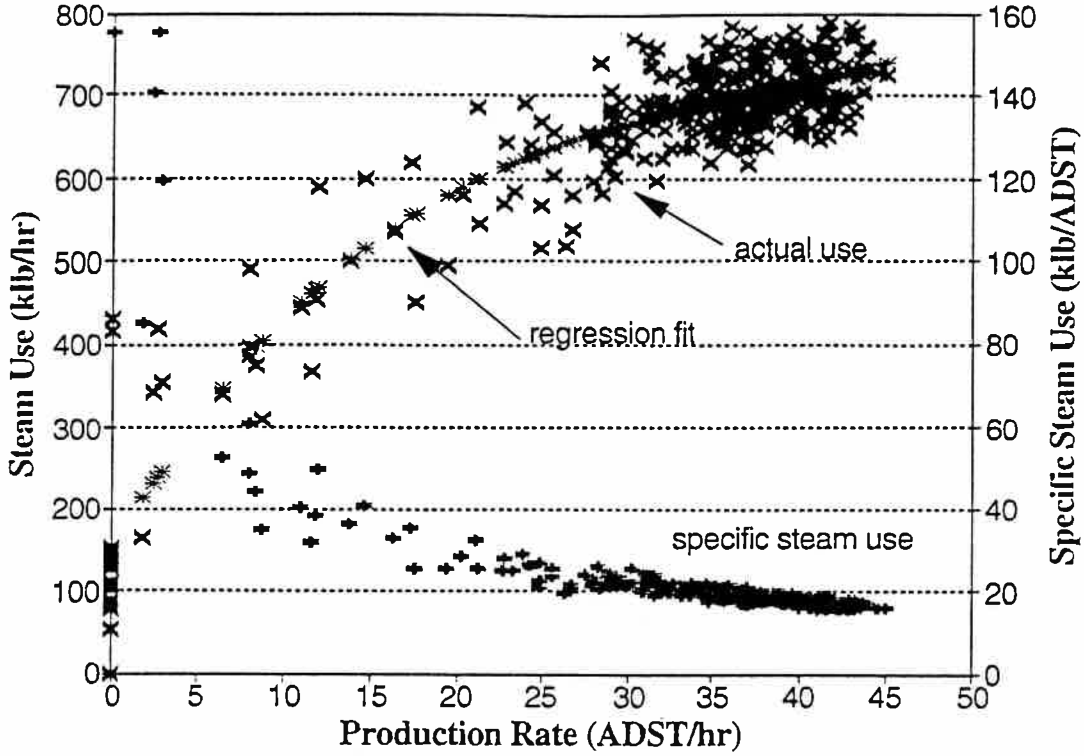

Figure 2. Steam use and specific steam use as a function of production rate.

DATA COLLECTION

Data were collected from the computerized real-time data collection system installed at the mill. The system takes data every 15 seconds and stores hourly averages. Data include mill-wide and unit-level (e.g., bleach plant, digester, dryer, etc) electricity and steam generation or consumption, unit level production rates, materials flows, temperatures, and pressures.

The data were analyzed to determine specific energy consumption (energy per ton of pulp produced) at the unit-level and for the overall mill. Fuel use in the lime kiln was not included. An important parameter in the analysis is the pulp production rate. High production rate operation, defined here as 34-43 ADST per hour, accounts for about three-quarters of mill operating time (Fig.1). Energy use data were critically analyzed for periods of high production rate with the expectation that they would show energy being used most efficiently during those periods. Data for the entire range of production rates were also analyzed to determine the energy impact of days when production rates fell outside of the 34-43 ADST per hour range. Unusually extreme values were excluded from the analysis.

Interpretation of the data was not straightforward. Outputs from the data logging system at the mill are routinely used to make process control decisions. Unit-level energy flows are generally not used, making suspect the accuracy of the energy metering equipment. Thus, the energy use data had to be verified through various independent means.

Another complication in the data analysis is the lag time between production rate and steam flow measurements. The production rate data (Fig. 1) are based on the pulp flow rate measured at some intermediate storage tanks. These flows may not correspond with the simultaneously measured unit-level steam flows. To minimize this lag-time error, the analysis here uses daily average energy consumption and production rates calculated from the hourly data. The analysis of electricity demand is less affected by the lag time error since electricity use changes less with production rate than does process steam use.

STEAM USE AT THE MILL

Steam use over one calendar year (1993) was analyzed to understand the usage patterns and to determine specific steam consumption (MMBtu per ADST) at the unit-level. Total specific steam consumption at the mill shows an expected decrease with increasing production rate (Fig. 2). Some of the variations in steam use for a fixed production rate are due to seasonal changes in energy use.

Table 1. Specific steam consumption in MMBtu per ADST for different operating periods.[a]

End Use	Winter, high production rates	Winter all days	Summer, high production rates	Summer all days	Fall&Spring all days	Annual average
High pressure steam (155 lb per in^2)						
Digester	3.90	3.98	3.78	3.83	3.96	3.93
Pulp dryer	2.94	3.00	3.07	3.05	3.05	3.08
Vacuum ejector	0.05	0.05	0.06	0.06	0.06	0.06
Utilities	0.89	0.94	0.79	0.86	1.00	0.95
O_2	0.03	0.03	0.26	0.28	0.11	0.14
Subtotal	**7.88**	**8.08**	**7.82**	**8.08**	**8.19**	**8.15**
Low pressure steam (55 lb per in^2)						
Pulp dryer	1.25	1.60	1.26	1.36	1.59	1.52
Profiler	0.46	0.48	0.46	0.50	0.49	0.49
Evaporator	3.64	3.86	3.41	3.57	3.60	3.66
Concentr.	0.74	0.80	0.85	0.88	0.89	0.86
Bleach plant	1.22	1.26	0.78	0.80	0.95	0.99
Utilities	0.30	0.32	0.20	0.22	0.30	0.28
O_2	0.22	0.24	0.21	0.22	0.23	0.23
Causticizing	0.28	0.29	0.17	0.19	0.28	0.27
Water heater	1.08	1.18	0.46	0.57	0.86	0.86
Chiller	0.52	0.56	0.93	1.01	0.91	0.85
Deaerator	2.12	2.24	1.72	1.87	1.98	2.01
Soot blow	0.86	0.91	0.89	0.94	0.89	0.91
Subtotal	**12.94**	**13.74**	**11.28**	**12.13**	**12.98**	**13.03**
Total	**20.82**	**21.84**	**19.10**	**20.21**	**21.17**	**21.09**

(a) June, July, and August data were taken to represent summer. December, January, and February data were used for winter.

Table 2. Correlation of steam use to production rate (R^2 values).[a]

End Use	Winter	Summer	Annual
Digesters	0.78	0.80	0.84
Evaporators	0.32	0.43	0.53
Concentrator	0.03	0.31	0.47
Bleach plant	0.55	0.37	0.53
Pulp dryer	0.66	0.52	0.76
Utilities	0.18	0.11	0.59
Chiller	0.01	0.14	0.36
Water heater	0.05	0.13	0.13
Deaerator	0.08	0.06	0.57
Total steam	0.80	0.80	0.89

(a) The R-squared values were determined by polynomial regression analysis. The higher R-squared value for total steam compared with individual end-uses suggests that there may be some canceling effects between high and low steam use at different unit-level operations. The higher R-squared value for annual data compared with winter or summer data is partly resulting from the fact that the annual data are spread over a broader range of production rates. It does not mean that there is less variation in steam demand for a fixed production rate.

Seasonal unit-level specific steam consumption is summarized in Table 1. Steam use is nearly 10% higher in the winter than in the summer. Table 1 also indicates that the digesters and the pulp dryer are the highest users of high pressure steam. Together with the evaporation plant (including the concentrator) they account for 62% of annual average total steam demand.

Regression analysis was conducted to examine correlations between daily average unit level steam consumption and whole-mill production rate. Such correlations can be useful in monitoring and evaluating process energy use, and as indicators of process energy efficiency, by comparing actual to expected consumption. Table 2 shows the calculated R-squared values at the unit-level for some uses and for the whole mill. The highest R-squared value is for total steam demand using annual data. At the unit level the highest values are obtained for the digesters and pulp dryer. These are fiber-line operations where it is expected that steam demand will closely follow changes in production rate. The overall relatively low R-squared values, however, show that equations determined from this regression analysis would not be useful for predicting steam demand.

The variation in steam use for a fixed production rate, leading to the low R-squared values, is in part, as discussed earlier, due to lag times between production rate and energy flow. A rough estimate of the storage capacity between different process stages indicated that intermediate storage tanks cannot account for more than a small part of the variations observed in steam use. The variations in steam use suggest that the steam system may not be carefully controlled. Unfortunately, no comparable data from other mills have been found in the literature to establish whether variations in steam demand as in this mill are unusual or common. The results, however, suggest that more detailed unit-level analyses of energy and material flows be undertaken to help explain the variations and at the same time identify potential improvements.

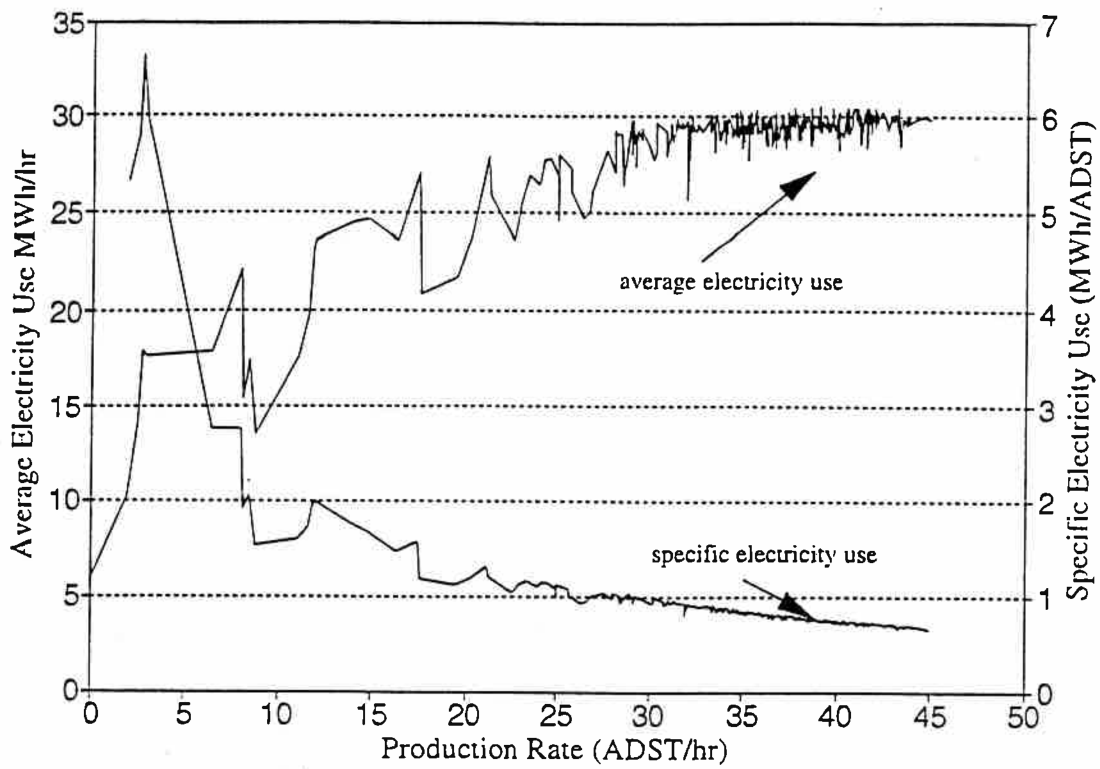

Figure 3. Electricity use and specific electricity use as a function of production rate.

Table 3. Specific electricity use and correlation of electricity use to production rate.

End use	High production rate kWh/ADST	Annual average kWh/ADST	Annual data R^2-value[a]
Digesters	183	192	0.93
Bleach plant	157	168	0.96
Pulp dryer	144	158	0.82
Utilities	135	149	0.88
Caustic plant	53	60	0.54
Water plant	35	40	0.78
Lime kiln	60	68	0.64
Total	767	835	0.95

(a) R-squared values from correlating annual average electricity consumption to production rate using polynomial regression.

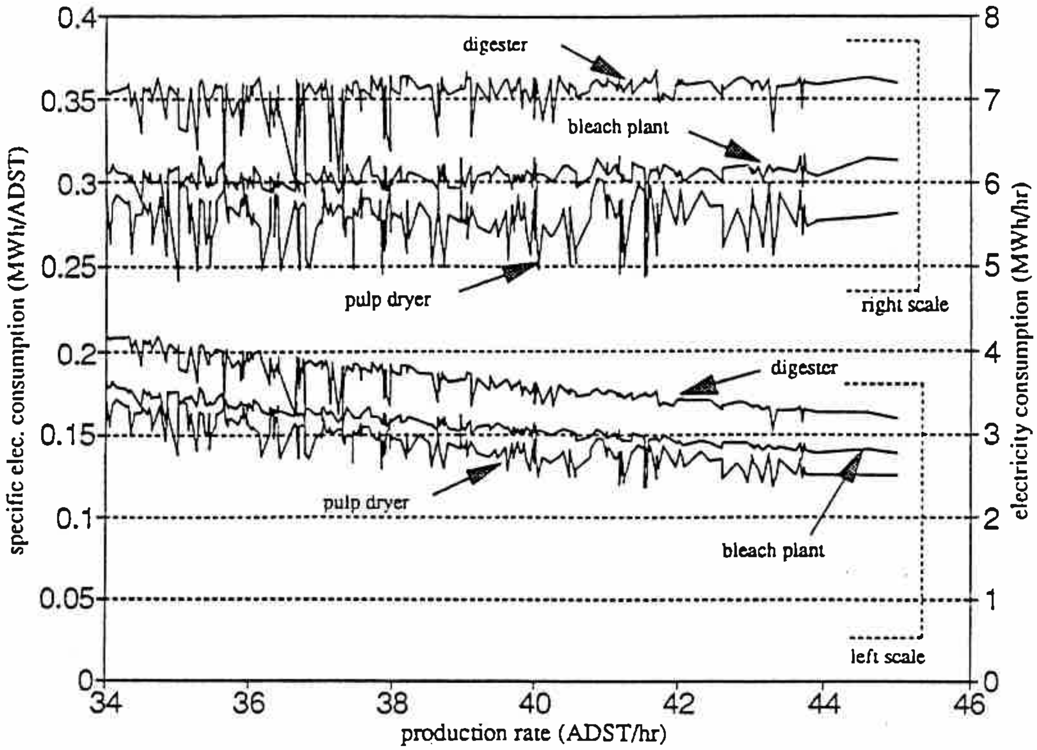

Figure 4. Electricity use and specific electricity use as a function of production rate for digester, bleach plant, and pulp dryer at high production rates.

ELECTRICITY USE AT THE MILL

Unlike steam use, electricity use at the mill shows no seasonal variations. Specific total electricity consumption at the mill was observed to decrease with increasing production rate (Fig. 3). Unit-level and total specific electricity consumption at high production rates are lower than the annual average (Table 3). Regression analysis based on the annual data shows a high correlation between average daily unit-level electricity use and production rate, except in the caustic plant and the lime kiln. These chemicals recovery cycle operations appear to be less dependent on production rate than the unit-level operations in the fibre-line.

Fig. 4 shows the variation and decrease in specific and total electricity consumption with production rate for digester, bleach plant, and pulp dryer. Note that total electricity use in these unit operations is essentially constant over the production rate shown. Total mill electricity consumption is also relatively constant at high production rates (Fig. 3).

Pumps and fans typically account for 40-45% and 15-20%, respectively, of total electricity use in kraft pulp mills (16). The flat total power consumption with changing production rate indicates that pumps and fans are operating with throttle control (power demand in pumps and fans at reduced flow is essentially the same as power demand at full flow when throttle flow control is used). Power demand would decrease with reduced flow if variable speed control were used.

ENERGY EFFICIENCY IMPROVEMENTS

Steam and electricity demands at the particular mill under study are high compared to other bleached kraft pulp mills (Table 4), suggesting that there is considerable scope for improving energy efficiency. Energy savings can be achieved in the short term through better insulation, plugging steam leaks, better process control, etc. However, much larger savings are likely through more far-reaching equipment and process modifications. Preliminary estimates of the potential energy savings in the mill are made here based on the results from the energy analysis and a survey of alternative process technologies. This is done with a view to understanding the potential changes in electricity to steam ratios, especially in the context of considering advanced cogeneration technologies.

Table 4. Comparison of specific energy use in kraft pulp mills

Mill	Steam, incl. powerhouse (MMBtu per ADST)	Electricity, including powerhouse (kWh/ADST)	Steam, excl. powerhouse (MMbtu per ADST)	Electricity, excluding powerhouse (kWh/ADST)	Electricity to heat excl. powerhouse (kWh/MMbtu)
This study[a]	21.1	835	19.2	687	36
1980 U.S. mill[b]	17.4	708	14.0	595	42
Average 1988 Swedish[c]	13.1	762	-	671	51[d]
Best 1988 Swedish[c]	10.7	653	-	581	54[d]
Model mill 2000[e]	6.7	581	6.7	535	80

(a) Powerhouse electricity consumption is assumed to be equivalent to "utilities" (see Table 3). Electricity use in the woodyard for this mill could not be included. The powerhouse steam use in the mill in this study is taken as "utilities" high pressure steam and "soot blow" (see Table 1).
(b) Data for modern U.S. mill are from (15).
(c) Steam data for average and best 1988 Swedish mills. Swedish data were collected by ÅF-IPK on behalf of the energy committee of the Swedish Pulp and Paper Association (25).
(d) Electricity to heat ratio is based on steam demand including powerhouse because separate estimates of powerhouse steam consumption were not available.
(e) Data for the model mill 2000 is from a report by ÅF-IPK (31) to the Swedish Board for Technology Development. The model mill shows what is considered to be technically and economically feasible in a greenfield mill with 2000-vintage technology.

Short Term Potential

We have identified several possibilities for changes to the mill that could be made in the short term to reduce energy consumption (Table 5). Average specific energy use might be reduced if the plant were able to operate consistently at high rates of production, which is not the case today (Fig. 1). If the mill were to consistently produce in the range of 34-43 ADST per hour we estimate that annual steam and electricity demand could be reduced by 8% and 9%, respectively. The fluctuations in steam demand even at high production rates suggest that the potential savings through more precise energy control may be even greater. For our estimate of the short term savings potential we assume that operating at high rates of production and more precise energy control could save 10% of steam and electricity consumption (Table 5).

In addition to maintenance practices to minimize leaks and losses, the steam economy at the mill could be improved through increased condensate return. Condensate is presently returned from the major steam users, i.e., digesters, evaporators, concentrator, pulp dryer, and water heater, and the fraction returned varies between 60% and 88%. We estimate that the total condensate return could be increased by 10-15%, primarily from increased condensate from the pulp machine and some other mill processes which currently do not return condensate. This would result in a 1.2-1.7% reduction in mill wide steam demand (Table 5).

The annual average steam consumption in the drying section is 4.60 MMBtu per ADST (Table 1). According to a detailed study of energy use in kraft pulp mills, 2.8 to 3.0 MMBtu per ADST is considered typical for 1970s-vintage technology (14) and an achievable level as low as 1.85 MMBtu per ADST has been suggested for 2000-vintage technology (31). The amount of water that must be evaporated in the dryer is a critical parameter. The moisture content is typically 55-65% entering and 10% leaving the dryer (20). A modern dewatering machine can reduce the moisture content to less than 50% before the dryer (5). We assume that steam demand in the drying section can be reduced by 35% to about 3.0 MMBtu per ADST, primarily as a result of improved pressing before the dryer.

Table 5. Estimated energy savings and resulting energy use from potential short and long term retrofits and modifications.

Retrofits/ modifications	savings	Steam demand (MMBtu/ADST)	Electricity (kWh/ADST)	El./Steam (kWh/MMBtu)
Present consumption	-	**19.23**	**687**	**36**
Operation at high production rate	10% of steam 10% of electricity	17.30	618	36
Condensate return	1.5% of steam	17.04	618	36
Drying section retrofit	1.55 MMBtu/ADST	15.49	618	40
Pinch analysis	15% of steam	13.16	618	50
Electricity conservation[a]	10% of electricity	13.16	556	42
Short term potential		**13.16**	**556**	42
Digester retrofit/replacement	1.72 MMBtu/ADST	11.44	556	49
Emissions red. and closed cycle operat.	15% increase in electricity demand	11.44	640	56
Evaporators replacement	1.72 MMBtu/ADST	9.72	640	66
Long term potential		**9.72**	**640**	**66**

(a) Increases in electricity demand from steam saving measures (e.g., new condensate pumps) are assumed to be offset by electricity conservation measures that result in savings above the assumed 62 kWh per ADST, or 10%, indicated here.

A heat integration analysis at the mill would likely identify steam saving opportunities. No such analysis has been undertaken for this mill but results from pinch analyses at other mills have identified significant savings potentials. For example, one mill in Sweden uses 13-14 MMBtu per ADST of steam and has a process configuration similar to the mill studied here (23). Despite the already low steam consumption at the Swedish mill, a pinch analysis identified cost-effective opportunities to reduce steam demand by 1.2 MMBtu per ADST, or about 9%. Pinch analyses for a U.S. mill indicated savings of 28% in steam demand in winter and 15% in summer (11). In other cases, savings of 10-35% have been reported as typical for retrofits (6,11). Given the high present level of steam use at the mill under analysis here and the evidence that pinch analysis can often identify steam saving opportunities, it seems reasonable to assume that at least a 15% reduction in steam use could be achieved through implementing the results of a pinch analysis (Table 5).

Most of the electricity in the mill is used in electric motors that drive pumps, fans, compressors, mixers, and other machines. A preliminary examination of loading on motors (using ampere loading data from the computerized data collection system) indicates that many of the motors are operating at part load, which is consistent with other published results of detailed audits showing motor oversizing to be widespread in industrial pumping and air-handling systems, including those in the pulp and paper industry (16). One study of three mills in the U.S. showed that throttling losses in pumps varied from 10% to 80% of input power (11) and similar results have been reported by others (3). Downsizing motors and pumps, or installing variable speed drives if the oversizing is needed to keep a safety margin,

Table 6. Electricity savings potential estimated for 12 pumps based on measurements at a pulp and paper mill in Wargoen, Sweden, based on (19) as presented in (16).

Pump application and capacity (kW)	Recommended investments[a] M	P	TI	VSD	Investment cost (k$)[b]	Annual savings (MWh/yr)	CSE[c] (c/kWh) for discount rate of 6%	20%
Raw-water intake (119)	X	X			44.3	475 (50%)	1.3	2.2
Wash water (380)		X		X	86.2	550 (18%)	2.1	3.6
Tank drainage (69)				X	29.2	216 (42%)	1.8	3.2
Bleached pulp (36)		X			8.9	43 (31%)	2.8	4.9
Return water (101)	X	X		X	85.8	610 (68%)	1.9	3.4
Warm water filtration (54)	X	X			19.1	192 (40%)	1.4	2.4
Mixing (184)	X		X		32.3	331 (23%)	1.3	2.3
Fresh water supply (59)	X	X			14.9	414 (82%)	0.5	0.9
Effluent (28)	X	X			13.1	130 (57%)	1.4	2.4
Paper machine water (28)				X	13.4	162 (79%)	1.1	2.0
Mixing tank (26)				X	13.4	153 (78%)	1.2	2.1
Waste water (52)			X		5.2	200 (48%)	0.4	0.6
TOTALS	6	7	2	5	**365.8**	**3476 (38%)[d]**	**1.4**	**2.5**

(a) M = replace motor, P = replace pump, TI = trim pump impeller, VSD = install variable-speed drive.
(b) Costs are given in thousand 1990$. Original costs in Swedish kronor (SEK) were converted using 6.5 SEK per U.S. dollar. The present exchange rate is approximately 7.5 SEK per U.S. dollar.
(c) Cost of saved electricity (CSE) calculated assuming 10-year lifetime. CSE is calculated as the annualized capital costs divided by the annual electricity savings.
(d) The savings represent 26% of the electricity used by a total of 32 pumps that were originally selected for this study. Detailed savings estimates were made only for those listed in this table.

typically result in savings of the order of 10% to 50%, but VSD savings as high as 80% have been reported (Table 6). We estimate that these and other electricity conservation measures can reduce electricity demand by about 60 kWh per ADST in the short term, above what is needed to offset increases in electricity use that might arise from implementation of steam saving measures.

The economics of the various energy efficiency measures indicated in Table 5 are not examined here. However, most of the measures we discuss have been shown to be cost-effective in other mills (11,19,23). The estimated cost of saved electricity (CSE) shown in Table 6 illustrates this for some pumping system retrofits at one mill in Sweden. Thus, while an examination of the economics is obviously a prerequisite to implementation of efficiency improvements at the present mill, it appears that with the limited set of measures considered in Table 5 for short-term improvements, total steam and electricity demands could be reduced by 32% and 19%, respectively.

Long Term Potential

Retrofits involving more far-reaching process changes could have still greater impacts on reducing energy use. The extent to which some of the technologies discussed here are introduced in practice will be dictated primarily by considerations other than energy efficiency. For example, such retrofits and changes may be driven by consumer demand for a certain product quality, environmental regulations, overall production cost reductions, or, as in most cases, combinations of the above. In any case the technology options for any given mill are large. The mill under study here serves to illustrate some options and the potential for energy efficiency improvements.

Pressures to reduce the environmental impact of mill operations is motivating changes in the fiber line from the digester to the pulp dryer. A particular driving force has been an interest in reducing emissions of chlorinated organic compounds, including dioxins, associated with the bleach plant. This has stimulated the development of bleach processes that are elemental chlorine free (ECF) or totally chlorine free (TCF). Closing the bleach plant and other water use cycles in order to minimize the overall environmental impact is an ultimate goal (22). Modified cooking strategies to extend the delignification of the pulp in the digester and thereby reduce the need for subsequent bleaching is a key technology. Extended delignification, and improved pulp quality compared to traditional processes, can be achieved in both continuous and batch digesters. Modified cooking involves greater control of the alkali concentration during the cook and altered sulphur chemistry.

New batch processes were developed during the 1980s primarily to reduce digester energy demand since the conventional batch process consumes about twice as much energy as the continuous process. It was discovered that displacement heating in combination with pretreating the wood chips with black liquor significantly improves pulp quality (10). Energy savings ranging from 30% to 78% have been reported for mills with batch digesters that have converted to displacement processes (7,28,30). Heat demands as low as 1.5 MMBtu per ADST have been reported (17). Digester steam demand in the mill under consideration here is 3.9 MMBtu per ADST (Table 1). We assume that retrofitting or replacing the digesters could reduce steam demand by 1.72 MMBtu per ADST (Table 5).

Modified cooking with extended delignification, followed by oxygen delignification, makes it possible to achieve high pulp brightness without using chlorine or chlorine dioxide. As a result the bleach plant can be operated as a closed cycle (some mills are now taking measures to do this), with the organics in bleach plant effluents utilized in the recovery boiler, increasing its energy output. However, the load on the evaporators and the recovery boiler, the capacity-limiting bottlenecks in many mills, also increases. Closed-cycle operation also means that various trace elements in the wood that are now discharged with the effluents must be purged at certain points in the process so as not to accumulate (8).

New electricity end-uses may be added to the process as a result of measures to improve the environmental performance. These include oxygen and ozone generators, and increased process- and waste-water treatment. Closed-cycle mill operation, on the other hand, would result in less water being used in the process so that the total pump-work may decrease. Increasing the consistency of the pulp which is pumped and processed can add to the reduction in pump-work. Comparisons of closed-cycle and conventional mill designs indicate that electricity use might be only about 15% higher in the closed cycle mill (8). A 15% increase in electricity demand is assumed for the calculations in Table 5. This increase can be partly offset by the greater electricity generation possible in the closed cycle mill, due to the higher loading of organics sent to the recovery boiler.

Steam use in the evaporation plant, where the solids content of the black liquor is raised to about 70%, is on average 3.66 MMBtu per ADST plus 0.86 MMBtu per ADST in the concentrator (Table 1). Replacing the existing 5-effect rising film evaporator with a 6-effect falling film evaporator could reduce steam demand by up to 30% (14,21). (Steam use for the model mill in Table 4 is 2.45 MMBtu per ADST for a 6-effect falling film evaporator with a superconcentrator. In the model mill the solids content of the concentrated black liquor is raised to 85%.) Steam demand can be reduced further by using vapor recompression or a heat transformer (a reversed absorption heat pump), although these options are more costly (1,6). Higher solids content in the black liquor increases the overall energy efficiency and reduces emissions of sulphur as the temperature in the lower furnace of the recovery boiler is increased (9). For Table 5 we assume that a reduction in steam demand of 1.72 MMBtu per ADST can be achieved through installing a 6-effect falling film evaporator.

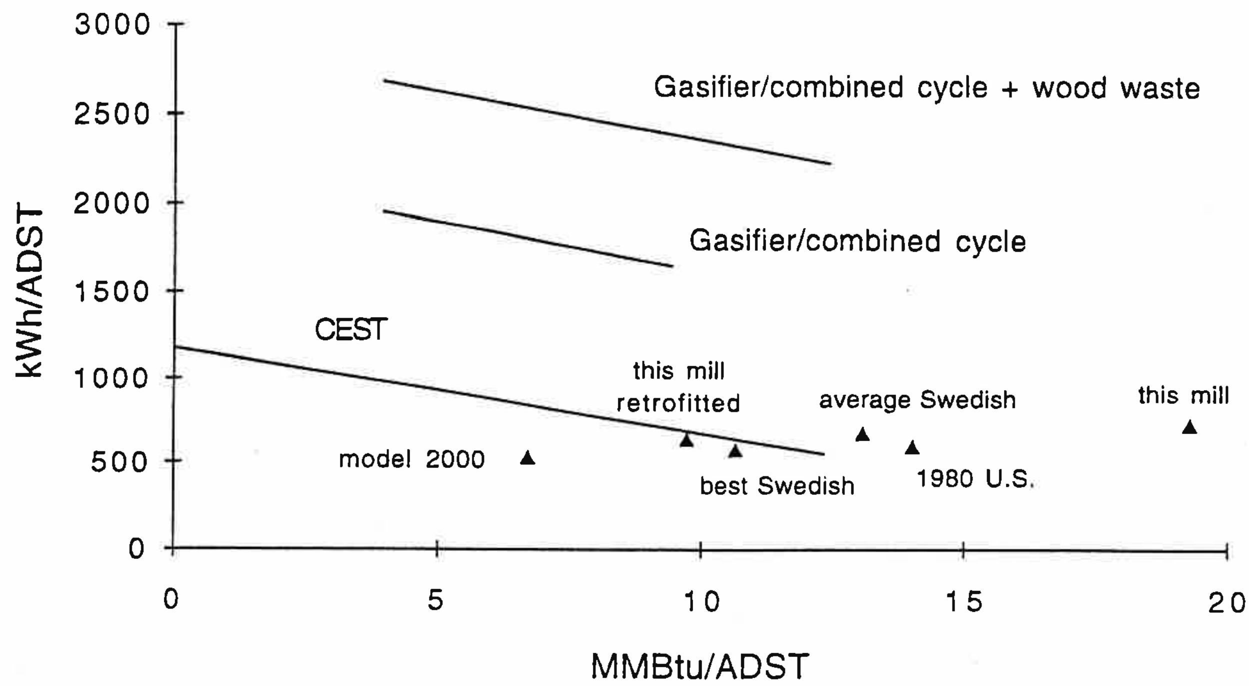

Figure 5. Steam and electricity production (net of the cogeneration plant) with bark (3.45 MMBtu per ADST) and black liquor (18 MMbtu per ADST) available from normal mill operation for a condensing extraction steam turbine and black liquor/bark integrated gasification gas turbine combined cycle. Also shown is an integrated gasification gas turbine combined cycle using an additional 6.9 MMBtu per ADST of gasified wood waste. For the condensing extraction steam turbine the following efficiencies are assumed: recovery boiler 67%, bark fuel boiler 85%, steam turbine 75% (isentropic), generator 95%. Steam inlet is at 870 psi and 842 F. Black liquor gasifier cold gas efficiency is 68% and the higher heating value of the gas is 125 Btu per ft^3 based on (13). Bark gasifier efficiency and combined cycle efficiency for bark and black liquor fuel gas is based on (4). Gas turbine exhaust is used to reheat the black liquor fuel gas to 662 F to emulate the same system as modelled in (4). Heat recovery steam generator exhaust inlet temperature is 882 F and outlet temperature 320 F. The 6.9 MMBtu per ADST of wood waste mass is equivalent to 20% of the pulp wood mass and is taken to represent the amount of logging residues that could be removed with the pulp wood. Data for actual and model mills from Table 4.

For the limited set of short- and long-term options considered here (Table 5), steam and electricity demand at the mill could be reduced by 49% and 7%, respectively, from present levels. Without closed cycle operation and other efforts to control emissions, electricity demand could be reduced by 19%.

COGENERATION

Steam raised in the recovery boiler at present meets only about half of the energy demand at the mill. Oil is burned to generate the balance of the steam and electricity requirements. The mill has little incentive to reduce steam consumption since a reduction in steam generation would reduce the power output from the existing back-pressure turbine, which in turn would require an increase in electricity purchases. However, with alternative cogeneration technologies in combination with steam savings, the mill could eliminate its need for purchased fuels. Near term alternatives include adding a condensing turbine after the back pressure steam turbine, or replacing the existing turbine with a condensing extraction steam turbine (CEST). The use of gas turbines fueled by gasified biomass or gasified black liquor--systems that are approaching commercial readiness--could meet on-site energy needs and generate excess electricity that could be sold.

Black liquor gasification technology (13,26,29) is essentially commercially ready for applications involving parallel operation with recovery boilers to boost chemicals recovery capacity. In the longer term, black liquor gasifiers are being developed to replace Tomlinson recovery boilers. In this context, black liquor gasification would offer several advantages to the Tomlinson boiler in addition to the potential export of electric power from the mill using gas turbines. Advantages include potentially lower investment cost, less emissions, reduced smelt-water explosion risk, and more flexibility in the chemicals output composition. Gasification processes are categorized as low temperature (1150-1400 F) or high temperature (1750-1850 F). They produce a fuel gas with a higher heating value of 100-125 Btu per ft^3 (air-blown gasifier) to 240-270 Btu per ft^3 (oxygen blown or indirectly heated gasifier). Some fraction of the sodium, sulfur, and other elements from the black liquor ends up in the fuel gas which must be cleaned in order to recover process chemicals and to prevent damage to downstream equipment.

Gasification and gas clean-up technology need further development and demonstration before they can be used with gas turbine cycles, but active work is ongoing in this area. Commercial systems could be available as early as the end of the decade. Black liquor gasification cogeneration system capital costs are not expected to be higher than for recovery boiler steam turbine systems, but they will be able to produce much more electricity (27).

To illustrate the impact of alternatives to the back pressure turbine in pulp mills, three alternatives for cogeneration at the mill were evaluated:

Option 1: a condensing extraction steam turbine (CEST) using available on-site fuels: black liquor (18 MMBtu per ADST) and bark (3.45 MMBtu per ADST, assuming that about 10% of the pulpwood brought to the mill is bark).

Option 2: an integrated gasifier/gas turbine combined cycle using the available on-site biomass fuels.

Option 3: an integrated gasifier/gas turbine combined cycle using the available on-site biomass fuels plus additional wood waste (6.90 MMBtu per ADST), corresponding to the estimated amount left in the forest as logging residues that can be recovered without detrimental environmental impact (15).

The increased energy content in the black liquor that could follow from closed-cycle operation of the bleach plant was not considered here.

The CEST, Option 1, in the full cogeneration mode (maximum process steam production), would generate 550 kWh per ADST and 12.4 MMBtu per ADST. The mill could be completely self-sufficient in energy if the retrofits that are shown in Table 5 were implemented (Fig. 5).

Option 2, the integrated gasification/gas turbine combined cycle in the full cogeneration mode would generate 1,630 kWh per ADST and 9.5 MMBtu per ADST (Fig. 5). In the mill retrofitted as in Table 5, there would be about 1,000 kWh per ADST, or 35 to 45 MW of baseload power, available for export from the mill (after meeting all process needs). The value of the electricity that could be sold, $50 per ADST at a sale price of, say, 5 cents per kWh, is significant in comparison to the value of the primary product, pulp. Present prices for market pulp are above $700 per ADST; in 1993-94, pulp prices were $400 to $500 per ADST. The same system combined with wood waste gasification (Option 3) would generate 2,220 kWh per ADST and 12.5 MMBtu per ADST in the full cogeneration mode.

CONCLUSION

The U.S. kraft pulp mill analyzed here purchases oil to meet nearly half of its energy demand. The analysis indicates that specific energy demand can be reduced by about 10% simply by operating at high production rates and more precisely controlling energy use. There is large scope for further reducing energy use through process modifications and equipment retrofits. The operational changes and technologies considered in this paper could potentially reduce steam use by 50%, and electricity use by 7% or 19% (depending on the extent to which measures to reduce emissions will increase electricity use). At reduced steam demands, black liquor and biomass gasifier/gas turbine combined cycle cogeneration systems provide a viable and environmentally attractive alternative to the back pressure steam turbine for meeting all mill energy needs. With such advanced cogeneration systems, the mill could likely generate 1,000-1,600 kWh per ADST of electricity in excess of on-site needs with no purchased fuel. For last year's pulp production at the mill, this translates into 290-460 GWh of excess electricity generation, and (for an electricity price of 5 cents per kWh) $50 to $80 of additional revenue per ton of pulp produced, or $15 to $23 million of total revenue annually.

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