Saving Electricity in Paper Manufacture: Measured Results for a Variety of Measures

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Much of the potential for cost-effective efficiency improvement in paper mills remains untapped. This is due in part to the lack of published information on potential savings, especially results of efficiency retrofits substantiated by measurements. This paper documents the results of measurements performed on several installations of measures to improve electrical efficiency in paper mills. The measures, installed through the programs of the NEES Companies retail affiliates, range from variable speed drives on process pumps to replacement of refining equipment.

For measures involving boiler pump and fan motors, it was found that boiler steam output was a good choice of independent variable with which to correlate motor performance. This variable is convenient to measure and is usually recorded on a regular and long-term basis at large paper mills. For one of the process measures, throughput in tons and fiber freeness factor were useful in normalizing savings. For another process measure, power did not correlate well with either of these variables.

Measurements performed before and after the retrofits, normalized by production levels, show substantial savings. Annual energy savings for VSDs ranged from 26% to 70%; savings for process measures were 50% to 60%.

INTRODUCTION

The paper industry ranks as the second most energy-intensive group in the manufacturing sector and consumes 12 percent of total manufacturing energy in the United States (Nilsson et al. 1995). In recent years much has been written about the benefits of various strategies for improving electric efficiency in paper manufacturing. Unlike in other industries, however, there is no systematic reporting of energy use, and relatively little has been published that documents the results of measured performance studies.

This paper documents the measured results of a number of installations of efficiency measures in three paper mills. The measures described here are not representative of the range of efficiency measures in the paper industry per se. Rather, these cases were chosen for several reasons: First, they illustrate a number of impact evaluation approaches which are likely to have broad application in the paper industry. Second, the savings for most of these measures are large as a percentage of pre-installation energy use. Third, the authors had well-documented before and after measurements for these installations.

The measures, installed under the efficiency programs of the NEES Companies retail affiliates, can be broadly classified into two groups:

Boiler Measures

- energy efficient motors and variable speed drives for boiler feedwater pump, forced draft fan, and induced draft fan

Process Measures

- energy efficient motor and VSD on whitewater pump
- refiner replacement
- stock preparation and transfer system modifications

Each of these projects was monitored before and after installation. The boiler and whitewater pump measures were studied for the purposes of technology assessment, whereas the remaining two process measures were monitored only for performance verification of savings already estimated using engineering analysis. A prime objective of each of the studies was to estimate monthly energy and demand savings (diversified and coincident with the utility's system peak) normalized to typical-year operating conditions for each application, based on short-term data collected at the site. In addition, the more ambitious technology assessments were intended to

- gain a better understanding of the factors influencing performance, and
- present the results as a function of an independent variable that could be used in the analysis of other installations without comprehensive monitoring

The latter studies required more extensive (and expensive) monitoring and analytical approaches than those used for performance verification. The approaches were tailored to suit each of the measures, and are described in detail below.

Boiler Measures

The performance and savings potential of boiler-related electrical efficiency measures was studied using instrumented measurements of installations serving a paper mill's main high pressure steam boiler. The boiler is used to provide steam to many of the manufacturing processes, as well as to a turbine for power generation. All three measures involved retrofitting boiler fans and pumps with variable speed drives and energy efficient motors. The boiler's feedwater pump, induced draft fan, and forced draft fan were all run at constant speed prior to the retrofit. Installation of VSDs allowed flow and/or pressure to be controlled more efficiently, by varying the speed of the motor rather than throttling the flow of water or air using valves or dampers. The impact of replacing motors with energy efficient ones was measured only for the fans, as the pump motor was replaced prior to the study.

At the onset of the case study, a measurement and analysis approach were devised with the objective of using short-term measurements to estimate performance over a typical year. The core of the approach was to establish, for each of the three boiler systems, pre- and post-retrofit correlations between a ''load variable'' (e.g., boiler steam production) and measured motor power. Selecting a load variable that is already monitored regularly and recorded by facility staff makes it possible to calculate demand and energy consumption for any time period. The monitoring need only be sufficient to establish this relationship over the full range of motor loads. Performance can then be normalized by selecting a load variable profile that is representative of a typical year.

The motor load for the three boiler systems is governed by the load on the boiler they serve. Several independent variables can be used as a proxy for boiler load: steam output, feedwater flow, and fuel oil consumption.[2] Although all three of these were already being measured at the study site, it was not clear at the onset which variable would most accurately represent load. To determine the most suitable load variable, all three were recorded at 15-minute intervals over the course of one week.[3] Based on analysis of this data, steam flow was chosen as the best load variable. Steam and feedwater flow were found to be well-correlated.

Steam flow was recorded continuously for two 4-week periods, one in winter and one in summer. We assumed that the steam load distributions measured for these two periods were representative, and applied them to historical monthly averages (correcting for holidays) to derive estimated monthly load profiles, shown in Table 1.

Feedwater pump. The 150 hp feedwater pump was retrofit with a VSD and new electronic pressure controller. Before the installation, a pneumatic control valve regulated feedwater pressure at 25 psig above boiler pressure. Once the VSD was installed, pressure could be regulated by adjusting motor speed. In addition to the variables described above, feedwater pressure was also measured, to enable correcting for changes in control set point. Steam flow, feedwater pressure, and true power were measured continuously for one week prior to and one week after the installation.

Forced draft fan. A 25 hp forced draft fan was first retrofit with an energy efficient motor and then a VSD. Before the installation, variable inlet vanes were modulated to maintain the required combustion air flow as measured by a pitot tube array at the fan inlet. The air flow set point was reset based on a signal from an electronic controller, which monitors steam flow, oil flow, and oxygen in the boiler flue gases. After the retrofit, air flow was regulated by adjusting motor speed with the inlet vanes locked wide open, using the same controller. In addition to the variables described above, the pitot tube signal was also measured, to confirm that air flow modulates roughly in response to boiler load. Steam flow, pitot tube signal, and true power were measured continuously for two weeks prior to the installation, one week after the motor replacement, and two weeks after the VSD installation.

Induced Draft Fan. A 40 hp forced draft fan was first retrofit with an energy efficient motor and then a VSD. Before the installation, variable inlet vanes were modulated to maintain the required combustion chamber pressure. After the retrofit, pressure was regulated by adjusting motor speed with the inlet vanes locked wide open. Steam flow and true power were measured continuously for two weeks prior to and two weeks after the installation.

Table 1. *Steam Load Distribution by Month (hours)*[a]

Steam Load Bin (1000 lb/h) From	To	Average Steam Load (1000 lb/h)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
0	**3**	1.5	0	0	0	0	2	0	2	0	1	0	0	0	4
3	**6**	4.5	0	0	0	0	0	0	4	0	3	0	4	0	11
6	**9**	7.5	7	1	0	0	4	0	2	0	2	0	16	6	37
9	**12**	10.5	17	22	0	0	2	0	1	0	2	0	4	18	65
12	**15**	13.5	2	2	0	0	1	0	2	0	1	0	1	2	11
15	**18**	16.5	0	0	0	0	1	27	2	0	2	0	46	1	80
18	**21**	19.5	48	0	0	0	2	153	12	1	3	0	2	47	268
21	**24**	22.5	1	1	0	0	2	506	50	21	31	0	1	1	614
24	**27**	25.5	1	1	0	0	16	33	372	57	122	3	5	1	612
27	**30**	28.5	4	7	3	6	28	0	288	307	461	26	12	4	1114
30	**33**	31.5	9	10	26	30	195	0	11	324	92	50	27	5	776
33	**36**	34.5	17	18	50	73	338	0	0	34	1	191	61	14	797
36	**39**	37.5	36	66	108	152	153	0	0	0	0	408	207	23	1152
39	**42**	40.5	72	128	382	341	2	0	0	0	0	65	157	63	1210
42	**45**	43.5	186	260	162	111	0	0	0	0	0	2	95	143	958
45	**48**	46.5	144	104	14	8	0	0	0	0	0	0	50	195	514
48	**51**	49.5	56	71	0	0	0	0	0	0	0	0	30	53	210
51	**54**	52.5	82	8	0	0	0	0	0	0	0	0	2	100	192
54	**57**	55.5	43	0	0	0	0	0	0	0	0	0	0	36	78
57	**>57**	58.5	19	0	0	0	0	0	0	0	0	0	0	31	51
		TOTAL	744	696	744	720	745	720	745	744	720	744	720	742	8784
		Avg. Load	42.3	41.5	39.4	38.7	33.3	21.6	26.0	29.3	27.4	35.7	36.5	43.1	35.0

[a] Based on 1992 boiler plant long data calibrated to field readings. Hours in each bin are rounded to nearest integer.

Analysis and Results—Boiler Measures

The savings in demand and annual energy use are included in Table 2.

Feedwater pump. Although we expected pump power to vary roughly with the cube or square of steam (and hence feedwater) flow, the pump curve is relatively flat in the region of operation. The measured data are shown in Figure 1, show this linear relationship. Linear regressions performed well, resulting in power curves which when combined with steam load distributions, yielded annual energy savings estimates.[4,5]

The VSD reduced the required power input throughout the range of observed operation. with a weighted-average reduction in power of 16.4 kW, or 26% of pre-retrofit power. This value can be taken as both a summer and a winter coincident demand reduction. Although steam loads during the utility's winter peak demand periods are considerably higher than those occurring during summer peak periods, demand reduction was relatively insensitive to steam load.[6] Normalized energy savings were about 144,000 kWh/y, or 963 kWh/hp-y over the range of operation in a typical year.

Measured data from the savings estimates spanned the range from 21 to 39 thousand lb/h of steam load. This range represents 50% of the steam produced annually. 82,800 kWh/y or 57% of the normalized projected energy savings are within the range for which we have measurements.[7]

Forced draft fan. Figures 2 and 3 show measurements of pre- and post-retrofit fan power plotted against steam load.

Table 2. *Summary of Estimated Energy and Demand Impacts for All Measures*

		Demand Savings[d]				Annual Energy Savings		
		Summer		Winter				% of Annual Pre-
Retrofit	hp	kW	kW/hp	kW	kW/hp	kWh	kWh/hp	Retrofit Energy[i]
Efficient motor, forced draft fan[a]	25	0.2	0.008	0.7	0.028	2,934	117	3.1%
Efficient motor, induced draft fan[b]	40	1.4	0.035	1.4	0.035	12,690	317	5.6%
Efficient motor, whitewater pump[f]	30	0.4	0.013	0.4	0.013	3,184	106	1.6%
VSD, feedwater pump[c]	150	16.2	0.108	16.2	0.108	142,321	949	26%[e]
VSD, forced draft fan	25	7.7	0.309	6.8	0.271	63,324	2,533	70%[e]
VSD, induced draft fan[b]	40	17.1	0.429	14.9	0.371	139,522	3,488	65%[e]
VSD, whitewater pump[g]	50	15.2	0.304	15.2	0.304	133,579	2,672	69%[e]
Refiner replacement[h]	450	156	0.346	156	0.346	1,280,429	2,845	62%
Stock prep. modifications	N/A	158	N/A	158	N/A	1,123,451	N/A	50%

[a] Savings for this installation may be overstated due to extrapolation beyond range of measurements
[b] Portions of savings attributable to the energy efficient motor and to the VSD are estimated from measured savings of the combination.
[c] Demand reduction for the feedwater VSD was relatively insensitive to steam load and represents weighted average demand savings for the year. The summer and winter coincident demand reduction are taken to be the same.
[d] Demand reduction is based on the maximum of the average monthly demand savings for each period, except for feedwater pump VSD.
[e] Percent savings for VSDs installed following the installation of energy efficient motors are savings as a percentage of energy use with the new motor.
[f] New motor is 30 hp. Savings estimates are probably not significant given statistical and instrument error.
[g] The 50 hp motor was replaced with a 30 hp motor prior to the installation of the VSD.
[h] The replacement refiner is 400 hp.
[i] Percentages are of pre-retrofit energy for the motors or systems themselves.

Figure 1. *Feedwater pump performance, showing measured data points and regression lines for throttling and VSD control.*

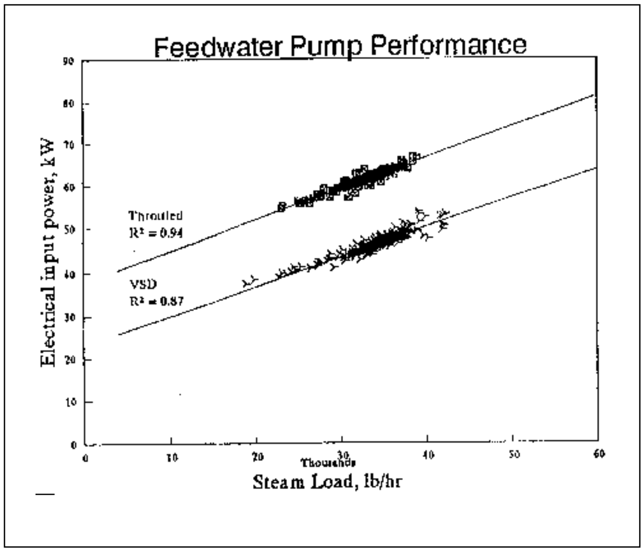
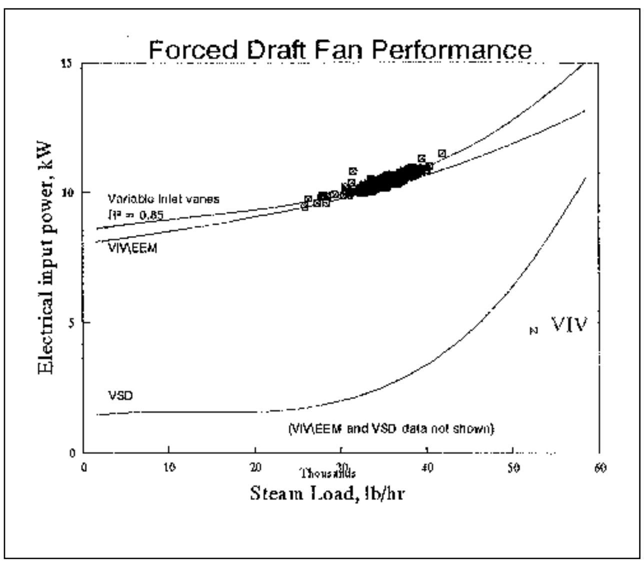


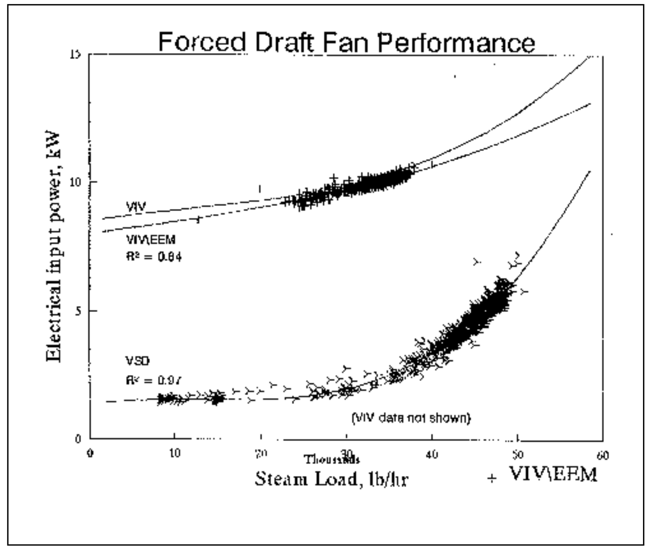
Figure 2. *Forced draft fan performance, showing measured data points for variable inlet vane control before motor replacement, and regression lines.*



Third-order polynomial regressions were used to determine power as functions of flow.[8] As was done for the feedwater pump, power curves were combined with flow distributions to yield annual energy savings.

The estimated weighted average reduction in power due to the motor replacement, calculated by summing the kWh savings in each steam load bin and dividing by the total hours of operation, is 0.30 kW. Annual energy savings for this 25 hp fan are projected at 3.1% of pre-retrofit consumption, or about 2,930 kWh/y. Due to the limited range of our data, we can be confident of 1,151 kWh/y in the mid-range of steam load (from 27 to 42 thousand lb/hr), which represents 55% of the annual steam production.[9]

Figure 3. *Forced draft fan performance, showing measured data points for variable inlet vane control after motor replacement (EEM = energy efficient motor) and VSD control, as well as regression lines.*

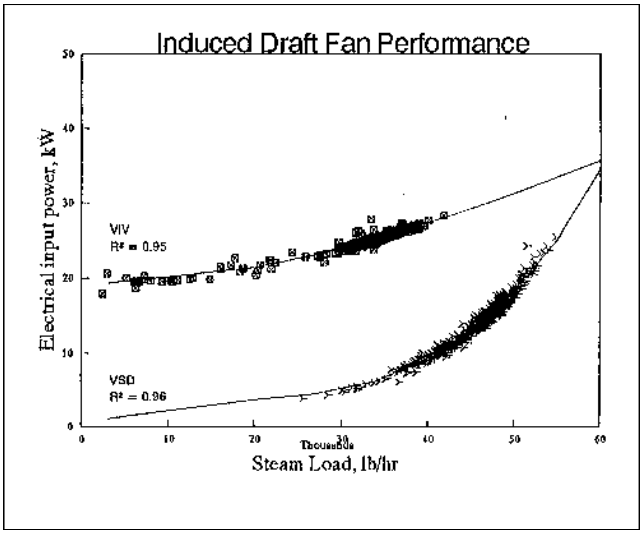


The weighted average reduction in power due to the VSD was estimated to be 7.2 kW, or 0.29 kW/hp, a reduction of 70%. Unlike the results for the feedwater pump, the power reduction observed for the forced draft fan VSD was significantly higher in summer than in winter. Coincident demand impact was therefore calculated separately for summer (June to September) and winter (December through February) periods, as 7.7 kW (81% of EEM power—i.e., power with the energy efficient motor in place) and 6.8 kW (57% of EEM power). These coincident demand savings represent the greatest of the monthly average demand savings in each period. The summer maximum demand impact occurred in July, August, and September, and the winter maximum demand impact occurred in February.

Annual energy savings for the VSD are projected at 63,000 kWh/y, or 2,530 kWh/hp-y, a reduction of 70%.[10] Of this amount, 50,700 kWh/y are within the region of steam load from 9 to 42 thousand lb/h for which we have measured data.

Induced draft fan. Figure 4 shows measurements of fan pre- and post-retrofit fan power plotted against steam load. Third-order polynomial regressions were used to determine power as functions of flow.[11] In the case of the VSD, the regression was forced to go through zero rather than allow it to dip below zero at low loads due to the lack of data.[12] As was done for the feedwater pump, power curves were

Figure 4. *Induced draft fan performance, showing measured data and regression lines for variable inlet vane and VSD control.*



combined with flow distributions to yield annual energy savings.

We were not able to obtain measurements after replacement of the motor and before installation of the VSD. The estimated weighted average reduction in power due to the combination of motor replacement and VSD, calculated by summing the kWh savings in each steam load bin and dividing by the total hours of operation, is 17.3 kW. Projected annual energy savings for the retrofit combination for this 40 hp fan are estimated at 67% of pre-retrofit consumption or 152,000 kWh/y.[13] Approximately 68% or 104,000 kWh/y of these savings are estimated from within the region for which we have data. Our measurements spanned the steam load bins from 24 to 42 thousand lb/h which represents 65% of the annual steam production.

Using rated efficiencies, we estimated a constant power reduction of 1.4 kW due to motor replacement, and subtracted this from total savings to yield savings due to the VSD. Annual energy savings for the motor alone are estimated to be about 12,700 kWh/y, or 317 kWh/hp-y. The weighted average demand savings from the VSD alone are 15.9 kW for the year, and range from 12.8 to 17.1 kW on a monthly basis. Annual energy savings for the VSD alone are projected at about 140,000 kWh/y, or 3,490 kWh/hp-y.

Like the results for the forced draft fan, the power reduction observed for the induced draft fan VSD was significantly higher in summer than in winter. Coincident demand impact was therefore estimated separately for summer (June through September) and winter (December through February) periods, as 17.1 kW (78% of estimated pre-VSD power) and 14.9 kW (55% of pre-VSD power). These demand savings represent the greatest of the monthly average demand savings in each period. The summer maximum demand impact occurred in August and September, and the winter maximum demand impact occurred in February.

Process Measures

Whitewater pump. This process pump delivers whitewater[14] from a tank at atmospheric pressure to a remote, open, whitewater tank and to vibrating screens. Assuming that the level of liquid in the 25-foot high inlet tank normally varies between 5 and 20 feet (depending on inflow and outflow, which are not correlated), there would be a net positive 5- to 20-foot head at the suction side of the pump, since the discharge lines drop to floor level before discharging to the atmosphere. The pump runs continuously. Prior to the VSD retrofit, flow was controlled by a discharge valve at the remote whitewater tank.

An old 50-hp motor was replaced with a 30-hp energy-efficient motor and variable speed drive.[15] After the VSD was installed, the same valve was used to control pump flow to the whitewater tank and a new pressure sensor was added to the discharge line near the whitewater pump to control pump speed to regulate pressure.

As with the boiler measures, the monitoring approach for the whitewater pump attempted to establish pre-retrofit and post-retrofit correlations between a load variable and motor kW. The only suitable variable, whitewater flow, does not vary predictably with any other measurable quantities, and plant personnel have kept no records it. For this study, we measured whitewater flow with a strap-on, transient, ultrasonic flow meter. Fifteen-minute measurements of pump motor power,[16] whitewater flow, whitewater header pressure, control valve signal, and VSD frequency were taken for three weeks before the retrofit, for one week after the efficient motor installation, and for one week after the VSD installation.

Preliminary data, taken on one-second intervals, confirmed a close correlation between flow and pump power. In addition, 15-minute kW readings taken simultaneously also exhibited a reasonable correlation with flow. The wide variation in flow from the subsequent sets of data, however, made us suspicious of the flow meter's accuracy. We chose pump discharge pressure and control valve signal as a proxy for whitewater flow.[17] This was done by regressing flow against these two variables using the data set for which they were well-correlated.[18]

Pump performance is shown in Figures 5 and 6. For the whitewater pump, we found that linear regression modeled the pre-retrofit condition well, indicating operation on the linear part of the pump curve.[19] Likewise, with data collected after installation of the energy-efficient motor, linear regres-

Figure 5. *Whitewater pump performance, showing measured data points for throttling control before motor replacement (EEM = energy efficient motor), as well as regression lines. ''GPM'' is a proxy for flow derived from pump discharge pressure and control valve signal.*

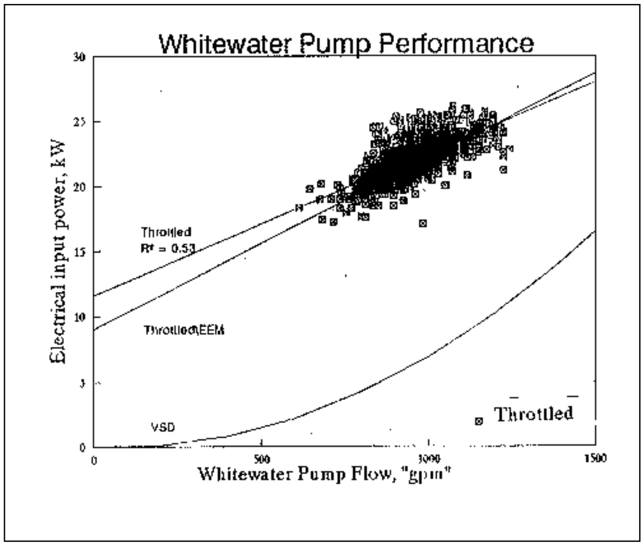
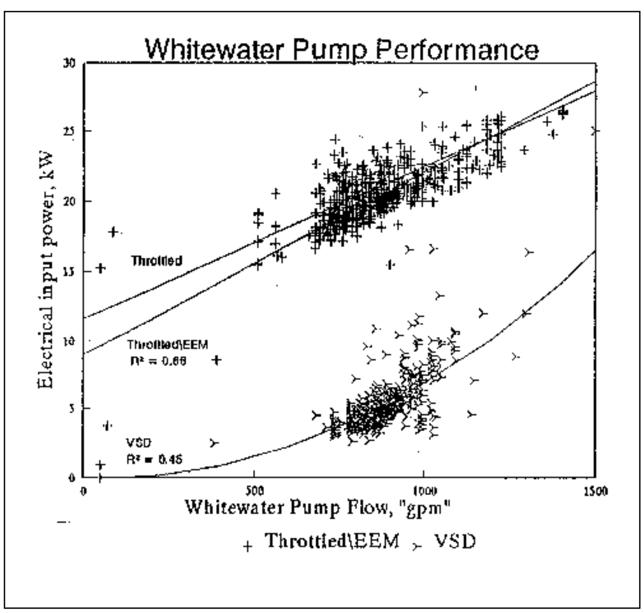


Figure 6. *Whitewater pump performance, showing measured data points for throttling control after motor replacement (EEM = energy efficient motor) and VSD control, as well as regression lines. ''GPM'' is a proxy for flow derived from pump discharge pressure and control valve signal.*



sion was appropriate. A second-order regression forced through zero was used for the VSD data.[20] The flow distribution measured during the monitoring period was assumed to be representative and combined with the power curve-fits to calculate annual energy savings. There was therefore no need to extrapolate the power curves, as was done for the boiler measures.

We calculated that the 30-hp energy efficient motor saved 0.4 kW at the average flow rate of 1,006 gpm.[21] Annual savings are estimated at 1.6% of consumption prior to the energy efficient motor retrofit, or about 3,200 kWh/y. Given the high scatter and overlap in the data sets, however, it is unlikely that these estimates are significant, although statistical and instrument error were not quantified.[22]

The VSD saved 15.2 kW at the average flow rate of 1,006 gpm, reducing consumption by 68.6% compared to the consumption following replacement of the motor. Annual savings from the VSD alone are projected at about 134,000 kWh/y.[23] These savings are summarized along with those of other measures in Table 2.

Refiner. A 200 hp conical (Jordan type) refiner and a 250 hp double disc refiner were replaced with a single triple-disc refiner with a 400 hp motor.[24] The new refiner gives the mill a larger throughput along with a higher degree of fiber treatment. The increase in energy efficiency is due mostly to the increase in refining surface area, which increases the inter-fiber and bar-to-fiber contact for a given flow rate and motor speed. The conical refiner was left in place for the purpose of refining cotton fiber one week per year.

Because refining energy use is proportional to two independent load variables—mass throughput and degree of fiber treatment—the monitoring and analysis approach was designed to normalize performance by these factors. As part of a savings verification project, true motor power was measured at 15-minute intervals for two weeks before and two weeks after the installation. Throughput measured in tons and degree of fiber treatment measured in Canadian Standard Freeness Drop (CSF) were recorded for each 8-hour shift.

The average throughput and CSF for the four weeks of measurement were thought to be representative of annual operation, and were therefore used as the basis for normalization. Pre- and post-installation measured energy use in kWh/ton-CSF were multiplied by the product of average throughput and CSF to yield normalized estimates of pre- and post-installation energy use. In addition, it was conservatively assumed that the conical refiner left in place would operate 10% of the time. Demand savings were estimated based on measurements taken during periods of utility peak coincidence.

The savings due to the refiner replacement were significant, and are summarized in Table 2. Annual energy savings based on the measurements are projected to be 1,280 GWh/y, or 2,845 kWh/hp-y. Summer and winter coincident savings are estimated to be 156 kW, or 0.35 kW-hp.

Stock preparation and transfer system modifications. This retrofit on an egg carton manufacturing process involved:

- consolidating three production lines into two by moving the point at which color is added to the pulp, enabling the elimination of stock circulation and transfer pumps (65 hp total), and

- installation of a PLC and automation controls to turn remaining circulator and transfer pumps (115 hp total) on and off, reducing run time.

Monitoring and analysis of savings were performed as part of a savings verification project. Measurements of true motor power for the pulper and pumps were recorded every 15 minutes for two weeks before and two weeks after the retrofit. In addition, the throughput in tons of pulp was recorded for each 8-hour shift, since this variable was thought to be a major determinant of load. For the pumps to be removed, two pumps totaling 35 hp were monitored. Because operation of many of the pumps was identical, it was possible to monitor only selected pumps and extrapolate the results to the others. For the pumps to remain under the new controls, two pumps totaling 30 hp were monitored.

Regressions of power vs. throughput proved unsuccessful, so average operation during the course of the monitoring was taken to be representative of the year. The annual projections based on the measurements, summarized in Table 2, show energy savings of 1,123 GWh/y, or 50%, and coincident demand savings of 158 kW.

CONCLUSIONS

Relatively short-term measurements were used successfully to estimate annual savings for a range of electrical efficiency measures in paper mills. Annual energy savings for the motor replacements were less than 6%. This is low enough relative to suspected measurement and analysis error to suggest that caution be used in generalizing from these results. Savings for the VSDs ranged from 26% to 70%, and savings for the additional process measures were in the 50% to 60% range. Weighted demand savings (coincident with the utility's system peak) of similar levels were achieved.

More thorough analysis of historical boiler steam data during the planning stage might have resulted in additional measurements of operation in the highest output range and given greater confidence in the results at that level for the boiler group measures. We recommend performing such analysis prior to measurements if possible, as a means of enhancing the significance of expected results.

Strap-on ultrasonic transient flow meters are often tried because of the obvious practical advantages that non-intrusive flow measurement has over installing in-line flow meters. As other studies have shown, their success often depends on the physical characteristics of the fluid and piping arrangement. For whatever reason, the meter used to measure whitewater flow in this study did not yield good results. Fortunately, pump discharge pressure and control valve position provided a satisfactory proxy for flow.

It was found that boiler steam output was a good choice for an independent load variable with which to correlate motor performance and savings for boiler pumps and fans. The variable is convenient to measure, and is usually recorded on a regular and long-term basis at large industrial facilities. For one of the process measures, tons throughput and fiber freeness factor (CSF) were useful in normalizing savings; for another, power did not correlate well with throughput.

The value of correlating and normalizing performance and savings with independent load variables as was done in these analyses cannot be overemphasized. First, for systems whose operation varies (especially non-linearly), such correlation can improve accuracy considerably over results derived using simple differences in power. For many of the measures described here, results based on single ''snapshot'' measurements or even averages over time would clearly have yielded quite different results. Second, correlation with load determinants provides a physical understanding of the system—an understanding that can be useful both in operating or designing such systems and in generalizing the results of energy efficiency measures to other similar installations with less need for comprehensive measurements. Finally, the use of production variables to normalize performance and savings measurements for industrial measures can make it possible to derive typical or ''normal year'' estimates in much the same way degree-days or bin temperature data have traditionally been used in the analysis of HVAC measures, and thereby eliminate bias resulting from the occurrence of idiosyncratic loads during the measurement period.

ACKNOWLEDGMENTS

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ENDNOTES

1. Mr. Englander was with New England Power Service Company when much of this work was done.

2. Although boiler load itself depended on (in order of influence) power generation, river water temperature, mill production, and outside air temperature, we focused on steam output, without regard to the influencing variables. According to plant personnel, these variables changed little from year to year; our rolling yearly analysis of historical data likewise showed steam flow to vary little from one 12-month period to the next. Steam load was also found to be independent of time of day, a finding pertinent to the estimation of demand impact.

3. This could be done conveniently by feeding signals from existing plant instrumentation into the dataloggers installed as part of the study.

4. Quadratic regression was attempted for the post-retrofit case, but the resulting power curve crossed the pre-retrofit line at 93 kW, only 80 percent of full load. Quadratic and cubic regression (also tried) have the disadvantage of physically unrealistic behavior outside the range of measurement.

5. Although savings estimates were corrected for differences in feedwater pressure control before and after the retrofit, the effect was small, amounting to less than 1 percent of pre-retrofit consumption.

6. Billing (i.e., customer monthly peak) demand reduction is not reported here, but was generally considerably less than coincident demand reduction.

7. Actual reduction in power in this region (up to the maximum of about 60 lb/hr) would be expected to be slightly less than that of the linear estimation (actual power curves converge), whereas power reduction below the range of measurements would be greater than estimated. Because the bulk of operation outside the range of measurements falls above it, the estimated savings are likely high. The pump is considerably oversized, however, and the power curves up to 60 lb/hr are therefore still quite linear, so the overestimation due to extrapolation is likely to be small.

8. The data measured before and after the motor replacement (but before the VSD) are sufficiently similar and contain enough scatter to overlap; demonstrated savings (1.8 percent at 35,000 lb/hr) are sufficiently small that instrument error (perhaps on the order of 1%) becomes a significant concern. The 95% confidence intervals do not, however, overlap; we can be fairly confident that the savings reported are statistically significant within the region of data.

9. Outside the region of data, the constant-speed regression lines diverge. This causes concern that savings may be overstated outside the range of data. Since the plant spends few hours at low steam loads, this divergence below the range of data is of little concern. Above the range of data, however, it is more troubling, because about 23% of the annual hours are spent above 42,000 lb/h.

10. Energy and demand savings from the VSD include the effect of losses due to the new isolation transformer installed with the VSD.

11. The data measured before and after the motor replacement (but before the VSD) are sufficiently similar and contain enough scatter to overlap; demonstrated savings (1.8% at 35,000 lb/hr) are sufficiently small that instrument error (perhaps on the order of 1%) becomes a significant concern. The 95% confidence intervals do not, however, overlap; we can be fairly confident that the savings reported are statistically significant within the region of data.

12. Normally in cases such as this where VSDs are installed on fans or pumps that must regulate pressure or work against a static head, the power curve would be expected to be positive at zero flow. In this case, however, the fraction of fan power required to maintain the relatively low pressure difference was small compared to the total, and since fan curves were not available, it was assumed to be zero. A better number to have used would be the estimated power loss due to the VSD, about 3% of full load power, or about 1 kW.

13. Energy and demand savings from the VSD include the effect of losses due to the new isolation transformer installed with the VSD.

14. Water used in the ''de-inking'' part of a recyling process, after it has been freed of ink.

15. An isolation transformer was also installed to isolate the electrical distribution from harmonics that may be generated by the VSD.

16. taken upstream of the new isolation transformer

17. For a given pipe and valve size, flow rate through the valve should be uniquely determined by pressure in the pipe and valve position.

18. $R^2 = 0.91$.

19. The scatter is due in part to the variation in tank water level and associated static head.

20. As for the induced draft fan, a positive value for the constant term such as estimated VSD losses of 3% full load power (0.7 kW) would have been more appropriate.

21. The units of flow here are not direct measurements, but those calculated using regressions of pressure and control valve signal, as described above.

22. In fact, the regression lines cross at approximately 1,200 gpm, which is at the edge of the range of flow for which we have data. While it is physically possible that the 30-hp energy efficient motor could consume more power than the 50-hp standard-efficiency motor at certain points on its load curve, this outcome reduces our level of confidence in the calculated savings.

23. Energy and demand savings from the VSD include the losses attributable to the new isolation transformer installed with the VSD.

24. The terms ''refining'' and ''beating'' are used interchangeably, and refer to a part of the stock preparation process used in the paper and pulp industry. In most cases beating refers to the action of rotating bars opposite a stationary bedplate as the fibers flow past perpendicular to the bars. Refining usually refers to the action carried out by disk-type refiners where the fibers flow parallel to the bar crossings. In both cases the objective is to modify the papermaking properties of the pulp fiber to suit the product being made. The operation can be batch or continuous.

REFERENCES

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