

ELECTRICITY USE PATTERNS IN COTTON GINS

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ABSTRACT. Energy costs are the second largest source of variable costs for cotton gins, with electricity accounting for 18% of variable costs. Energy use has typically not been a major consideration in gin design and previous studies of energy use have utilized instantaneous readings or aggregated season-long values. In this study, electrical energy use was monitored throughout the entire season for several gins across the cotton belt. Motor loads were recorded for gin stands, fans, cleaning machinery, module feeders, and bale presses. Power consumption and power factor were recorded at motor control center disconnects. The gins monitored in 2010 averaged 35.8 kWh bale⁻¹, slightly less than the annual average values reported in past surveys. Differences in electricity use between monitored gins were likely due to differences in layout and installed equipment. The primary factor affecting electricity use per bale at a specific gin was the processing rate. For maximum energy efficiency, cotton ginners should operate at full capacity as frequently as possible and avoid idling equipment for periods longer than several minutes.

Keywords. Conservation, Cotton, Efficiency, Electricity, Energy, Ginning.

Electricity costs account for 18% of a cotton gin's variable costs (Valco et al., 2009). Total energy costs (electricity and dryer fuel) are the second largest component of variable costs, after seasonal labor. A significant opportunity exists to improve gin profitability by reducing energy use. From 2000 to 2009, the average retail electricity costs for all U.S. consumers increased 45%, from \$0.0681 to \$0.0989 kWh⁻¹ (USDOE-EIA, 2010). Furthermore, energy costs are likely to increase due to future scarcity of energy sources and increased demand for energy. Higher energy costs emphasize the importance of improved energy efficiency at gins and increase the economic benefit of implementing conservation measures.

Previous research on gin electricity use has utilized instantaneous readings of current and other values or aggregated data from utility bills or periodic meter readings. These studies have provided benchmarks for gin managers and indicated the distribution of electricity use among gin functions. Basic recommendations for improving energy efficiency have been made by researchers and engineers. However, more comprehensive research is needed to understand causes of variation in

electricity use at gins and identify specific opportunities in gins for energy conservation. Specifically, electricity use needs to be monitored with high temporal resolution throughout the ginning season for individual motors in a gin.

OBJECTIVES

The goal of this research was to gain a greater understanding of electrical energy consumption patterns in cotton gins. This knowledge can be used to identify management practices that improve energy efficiency. The objectives of this research were to:

- monitor individual motor loads and total gin electricity consumption throughout a ginning season,
- identify factors significantly affecting electricity use, and
- quantify potential energy savings from implementing improved management strategies.

LITERATURE REVIEW

Researchers have measured energy use at gins since the 1930s. Although ginning capacity and connected power have increased significantly, the average energy use only varied from 40 to 56 kWh bale⁻¹ (Holder and McCaskill, 1963; Watson et al., 1964; Wilmot and Alberson, 1964a; Wilmot and Watson, 1966; Anthony, 1983; Funk and Hardin, 2011; Ismail et al., 2011). Recent surveys of gin energy use have shown a slightly decreasing trend (Griffin, 1980; Anthony, 1988; Mayfield, 1992; Mayfield et al., 1996; Mayfield et al., 1999; Valco et al., 2003; Valco et al., 2006; Valco et al., 2009). These past studies have demonstrated significant variation in energy use between individual gins, from less than 30 kWh bale⁻¹ to over 70 kWh bale⁻¹ (Holder and McCaskill, 1963; T.D. Valco, USDA-ARS, personal communication).

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The majority of electricity consumed at gins is used for materials handling, specifically by fans used for pneumatic conveying. Electricity use audits by Funk and Hardin (2011) found that 59% of the electrical energy used was for materials handling, similar to previous studies by Anthony (60%, 1983) and Wilmot and Watson (65%, 1966). Consequently, differences in materials handling between gins have been identified as a significant source of the variation in electrical energy use between gins (Stedronsky et al., 1941; Wilmot and Alberson, 1964a; Wilmot and Watson, 1966). While gin managers can take some simple steps to reduce fan energy use, such as reducing fan speeds and sealing leaks in pipes and separators, the quantity of energy used for materials handling is largely dependent on the layout of the gin plant. Modifying plant layouts is often not economically feasible.

Management can more easily improve operating efficiency, which likely has a significant effect on electrical energy use. Gins require nearly as much power when idling as operating at full capacity, primarily due to increased power consumption by centrifugal fans. Watson et al. (1964) found that idling gins required 79% of their operating power, while Wilmot and Watson (1966) calculated a value of 86%. Watson and Holder (1964) illustrated the relationship between electricity consumption per bale and operating efficiency, apparently based on the power used while idling, rated capacity, and power used at rated capacity (fig. 1). However, details of the model were not specified and the relationship between electricity use and operating efficiency was not verified with data collected from gins.

Gin electrical energy use and processing rate need to be monitored at frequent intervals at a gin to develop an accurate relationship between energy use and operating efficiency. Ismail et al. (2011) acquired average power

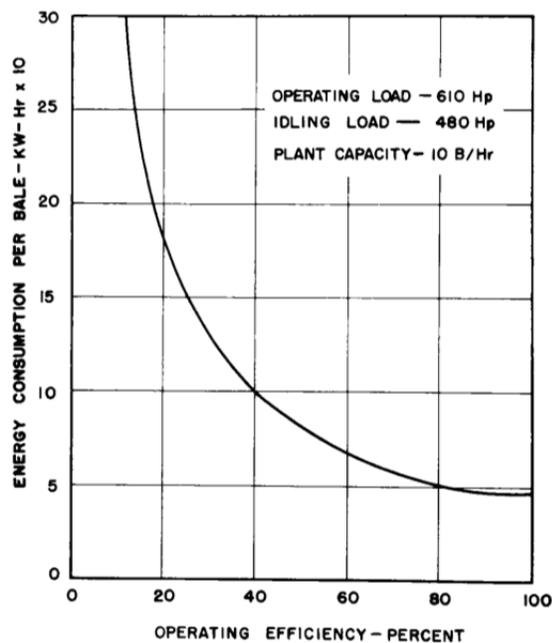


Figure 1. Relationship between electricity use per bale and operating efficiency (Watson and Holder, 1964).

readings at 15-min intervals from utility-installed meters at two gins in Australia. However, the relationship between power and processing rate was weak ($R^2 = 0.1973$). A likely explanation for this lack of correlation was that averaging power and processing rate over a number of bales obscured the variation in electricity use between individual bales. Individual motor loads were measured; however, readings were only taken every 5 min for one 12-h shift, and different motor loads were not measured simultaneously. Consequently, relationships between energy use for major ginning functions and processing rate were not developed.

An additional factor affecting gin electrical energy use is the cotton cultivar. Griffin (1984) found significant differences in power demand, energy use, and ginning rate between four cultivars with naked or semi-naked seed and a commercial fuzzy seeded cultivar. Anthony (1989) ginned 20 commercial cultivars and found that the total energy used by the gin stand varied from 35.7 to 51.1 Wh kg⁻¹. Boykin (2007) tested 65 cultivars and calculated a net ginning energy by subtracting the power required at idle from the total power and integrating over time. The net energy varied from 16.4 to 24.3 Wh kg⁻¹. Ginning energy was also negatively correlated with the USDA-AMS HVI (High Volume Instrument) measurements for uniformity index and strength and positively correlated with yellowness. Similar differences in ginning energy and ginning rate were observed by Bechere et al. (2011), but ginning energy was positively correlated with HVI strength and length measurements. Extrapolating these results to a commercial gin is difficult because these studies were all conducted on small-scale gin stands. Bechere et al. (2011) used a 10-saw laboratory gin stand, which is batch-fed. The other studies used a 20-saw gin stand with the gin stand feed control set to a constant speed. Commercial gins use an automatic feed control that maintains a constant load on the gin stand main drive or agitator motor.

Significant potential exists for energy efficiency improvements in cotton gins, as electricity use per bale has remained nearly constant for many years and large differences in electricity use exist between gins. Additional data is needed to better explain differences in energy use within and between gins. This information will also be useful in designing specific conservation measures and focusing future research efforts on reducing energy consumption.

MATERIALS AND METHODS

Electrical energy monitoring systems were installed in four saw gins during the 2010-2011 ginning season. Basic information about each gin is provided in table 1. The West region includes California, Arizona, and New Mexico; Southwestern states are Texas, Oklahoma, and Kansas; Mid-South states are located along the Mississippi River; and the remainder of the cotton producing states are in the Southeast region. The number of seed cotton cleaners refers to a single line of equipment (Gin D had split-stream seed cotton cleaning) and includes all cylinder-type cleaners and stick machines. Gin A had a single lint cleaner behind one

Table 1. Monitored gins.

Gin	Region	Primary Harvesting Method	Seed Cotton Cleaners	Gin Stands	Monitored Motors
A	Mid-South	Picker	3	2	29
B	Southwest	Stripper	6	3	38
C	Southeast	Picker	4	2	26
D	West	Picker	5	3	76

stand and two lint cleaners behind the other stand. All other gins had two complete stages of lint cleaning installed.

Sensors were installed to measure motor loads and total power consumption (table 2). Current transducers were installed at the disconnects on a single phase of all motors 11 kW (15 hp) and larger. Seed and lint cleaning equipment; gin stands; fans; and the bale press, trumper, and pusher pump motors were instrumented, as well as the disconnect serving the module feeder. To reduce instrumentation costs, motors driving droppers and augers were not individually monitored, except at gin D, where all motors were instrumented. All transducers were installed on the same phase to reduce the effect of any voltage imbalance on the data analysis. The current transducers were all split-core to facilitate installation and had 4-20 mA outputs to minimize the effects of electrical noise.

Power and power factor were monitored at gins A, B, and C. Potential transformers were installed on all three phases to record voltage at the gin. The line-neutral voltage was the input voltage for these transformers, except at gin B, where the line-line voltage was measured, since a corner-grounded delta electrical system was used. Flexible split-core current transformers were installed on all phases at each motor control center (MCC) disconnect. Both potential and current transformers had millivolt AC outputs. The sensitivity of the voltage transformers was 1.11 mV V^{-1} , while the current transformers had a sensitivity of 0.667 mV A^{-1} . The datalogger calculated power and power factor from the potential and current transformer data. Outdoor temperatures were obtained from nearby weather stations at gins A and C. Temperature was measured by thermocouple inside the gin building at gins B and D. The datalogger sampled and recorded all data at intervals between 2 and 5 s. The interval chosen was the minimum necessary to sample all inputs and varied between gins.

ANALYSIS

The current and power data was analyzed (Matlab R2009b, Mathworks, Inc., Natick, Mass.) to provide summary data for each gin and identify factors that significantly affected electricity use. For each record in the

data, total power demand by the gin was calculated. At gins A, B, and C, the measured power at each MCC was added to determine the total power. At gins A and B, a few additional motors were not connected to the instrumented MCCs. However, current was measured and the power consumed by these motors was estimated using the power factor measured at the gin. At gin D, voltage was measured while the gin was operating, and power factor was estimated using the average from the other gins. This voltage and power factor was used to estimate power demand from the measured motor currents. The total power calculated in this analysis did not typically include 120 V or 277 V loads, such as office equipment and lighting, since these loads were not connected to an MCC.

Power was allocated to the following ginning functions: seed cotton cleaning, ginning, lint cleaning, bale packaging, and materials handling. Seed cotton cleaning power was calculated from the measured motor currents for all cylinder-type cleaners, stick machines, and extractor-feeders in the gin. For gins A, B, and C, the monitored voltage and power factor at the MCC were used to calculate power, while the measured voltage and estimated power factor were used at gin D. Power for ginning included the total current of gin stands and agitator tubes (at two gins). Lint cleaning power included only lint cleaners. At gins A and B, all bale press equipment was located on a separate MCC; therefore, bale packaging power was measured directly. At gin C, the larger bale press motors were instrumented (press pumps, trumper pump, and pusher pump), and the power used by these motors was calculated. At gin D, all bale press motors were instrumented, and power was estimated from the current. Material handling included all other equipment in the gin: primarily fans, separators, droppers, conveyors, and module feeder motors. Power consumed by motors that were not instrumented individually was apportioned to the appropriate category based on motor nameplate horsepower.

A local maximum in the bale press pump motor current data indicated that a bale had been pressed. Average total and component power were calculated for each bale, along with the time required to produce the bale. The total and component electricity used for each bale was calculated by integrating the corresponding power demand over the length of time required to process the bale. All bales were used to calculate the average electricity use; consequently, the effect of gin downtime was included in this calculation of electricity use. Most gins try to produce 227-kg (500-lb) bales, although actual bale weight varies slightly and likely

Table 2. Instrumentation used in energy monitoring system.

Instrumentation	Input Range	Manufacturer	Model Number
Motor load	0-30, 0-60, 0-120 A	Veris (Portland, Ore.)	H921
	0-100, 0-150, 0-200 A	Honeywell (Minneapolis, Minn.)	CTP-20-200-AVG-001
	0-300 A	Veris	H321
VFD motor load (true RMS sensor)	0-100, 0-150, 0-200 A	Veris + Honeywell	H6810-300A-5A + CTP-20-005-AVG-001
		Honeywell	CTP-20-200-VFD-001
MCC voltage	0-300 V	Automation Direct (Cumming, Ga.)	ACTR200-42L-S
MCC current	0-500 A	Magnelab (Longmont, Colo.)	SPT-0375-300
Datalogger	-	Magnelab	RCT-1800-500
		Campbell Scientific (Logan, Utah)	CR1000
		Agilent (Santa Clara, Calif.)	34972A

affects the electricity use per bale. However, bale weights could only easily be obtained from one gin; consequently, electricity use per bale was not normalized for bale weight.

Individual motor current data were used to identify the power demand and time spent at idle. Idling was defined as all motors turned on and no cotton being processed through any gin stand. Total and component power demand and power factor were compared at idle and the maximum processing rate. The fraction of time each gin stand was idle was also calculated. The electricity ($E_{starting}$) consumed and time ($t_{starting}$) required in starting the gin were also determined. These factors, along with the power demand at idle (P_{idle}), were used to estimate a breakeven idling time ($t_{breakeven}$) according to the following equation:

$$E_{starting} * C_{electricity} + t_{starting} * C_{variable\ labor} = P_{idle} * t_{breakeven} * C_{electricity} \quad (1)$$

This analysis considered electricity use while idling and starting the gin, the variable labor cost ($C_{variable\ labor}$) incurred from the extra time required to restart the gin, and the electricity cost ($C_{electricity}$). This analysis also assumed that stopping and restarting the gin would require additional time equivalent to the gin's startup time. Stopping gin motors was assumed to require negligible time. The additional time actually required would likely depend on the specific procedures a gin follows for starting equipment and may be less for gins with control systems with automated starting sequences. Dryer fuel savings were not considered in this analysis, since these savings will vary considerably due to environmental conditions and temperature controller settings.

MODELING

Models were developed for predicting the power required and electricity used to produce a bale. These relationships were developed from the assumption that a gin uses a specific amount of power when idling (P_{idle}) and additional power consumed while processing cotton is linearly proportional to the processing rate (R). This processing rate is commonly expressed in units of bales h^{-1} . Operating at the gin's maximum processing rate (R_{max}) requires the maximum operating power (P_{max}), resulting in the following equation for the average power required to produce a bale:

$$P = (P_{max} - P_{idle}) * \frac{R}{R_{max}} + P_{idle} \quad (2)$$

Lower ginning rates may also be due to downtime, and the model accurately describes this situation if motors are left idling during downtime.

The electricity used per bale is the average power required for a bale divided by the processing rate. Dividing equation 2 by R yielded:

$$E = \frac{P_{max} - P_{idle}}{R_{max}} + \frac{P_{idle}}{R} \quad (3)$$

where E is the electrical energy required per bale (kWh bale⁻¹), power is measured in kW, and processing rate in bales h^{-1} . Using the parameters given in figure 1 by Watson and Holder (1964), equation 2 produces a nearly identical curve.

Ambient temperature was also used as a variable in the models describing material handling power and energy, total power and energy, and power factor. The power consumed by a fan is linearly proportional to the density of the air moved by the fan, and the air density is inversely proportional to the temperature. Over the range of temperatures encountered, the relationship of power and air density to air temperature is nearly linear; consequently a linear relationship was used in the model for simplicity and ease of interpretation.

Gins B and C varied the number of stages of lint cleaning used, based on the condition of the incoming seed cotton. At these gins, an indicator variable for the number of lint cleaning stages ($LC=0$ represented a single stage of lint cleaning, while $LC=1$ indicated two stages) was added to the models for lint cleaning power and energy, material handling power and energy (due to lint cleaner fans), total power and energy, and power factor. Gin A used only a single stage of lint cleaning and gin D used both stages during the entire monitoring period.

Preliminary analysis indicated that the power required reached a plateau near the maximum ginning rate. A possible explanation for the existence of this plateau was that the processing rate actually calculated from monitoring the bale press varied from the processing rate through the other ginning machinery. The bale press must accumulate a full bale of lint before it can be compressed, and actions of the press operators can affect the length of time of individual press cycles without influencing the upstream processing rate. Furthermore, this effect would be more noticeable at higher ginning rates. For example, a 5-s variation in press cycle time at 40 bales h^{-1} results in a larger variation in processing rate than at 20 bales h^{-1} . Because of this plateau, a piecewise model was used to describe the relationship between total power and processing rate:

$$P = \begin{cases} a_1 * R + a_2 + a_3 * T + a_4 * LC, & R < R_1 \\ a_5 * R^2 + a_6 * R + a_3 * T + a_4 * LC, & R < R_2 \\ a_7 + a_3 * T + a_4 * LC, & R \geq R_2 \end{cases} \quad (4)$$

where T was the temperature ($^{\circ}C$) and LC was the stages of lint cleaning used.

The first term in the piecewise model represented the linear region described by equation 2. The second term provided for a smooth transition between the linear region and the plateau. Enforcing constraints on the continuity of the function and the first derivative resulted in only five unique parameters, as a_5 , a_6 , R_1 , and R_2 were expressed in terms of the other parameters. The remaining parameters all have a specific physical meaning: a_1 equals $(P_{max} - P_{idle})/R_{max}$, a_2 is P_{idle} , and a_7 is P_{max} (with $T = 0^{\circ}C$ and $LC = 0$). Parameters a_3 and a_4 represent the contributions of temperature and the number of stages of lint cleaning used, respectively, to the power required.

Nonlinear regression was used to fit equation 4 to the average total power required per bale for each gin (*PROC NLIN*, SAS 9.2, SAS Institute, Inc., Cary, N.C.). Bales with power values less than the idling power identified for the gin were excluded from the analysis, since equipment was turned off for a period of time while the bale was produced. Equation 4 was also used to model power factor and the power required for different gin functions (with temperature and lint cleaning variables included as described earlier). The total and component energy use per bale predicted by the model was also determined by dividing the predicted power by the processing rate. The accuracy of this model in explaining variation in power, power factor, and electricity use per bale was examined.

CULTIVAR AND CLASSING DATA

Bale weights, USDA-AMS classing data, and cultivars were obtained from management at gin C. For data from gin C, analysis of variance was performed on the processing rate, average power, and electrical energy use per bale (*PROC MIXED*, SAS 9.2, SAS Institute, Inc., Cary, N.C.). Cultivar and the number of stages of lint cleaning were used as independent variables in the statistical analysis, while bale weight and ambient temperature were used as covariates in the mixed models for electricity use per bale and processing rate. The processing rate for each bale and ambient temperature were used as covariates in explaining the variation in power demand, to account for the difference in power consumption when the gin was operating at less than full capacity. For each combination of cultivar and the number of stages of lint cleaning used, correlation analysis (*PROC CORR*, SAS 9.2, SAS Institute, Inc., Cary, N.C.) was performed on the classing data and power and energy variables to identify significant relationships.

RESULTS AND DISCUSSION

Average electricity use per bale and power factor for each gin are shown in table 3. The average electrical energy used per bale was slightly less than the values reported from recent audits (40.1 kWh bale⁻¹; Funk and Hardin, 2011) and surveys (42.4 kWh bale⁻¹; Valco et al., 2009). The gins selected for energy monitoring had higher processing rates than the average reported from the survey data, which likely resulted in higher energy efficiency. The survey data was also based on utility bills; consequently, lighting and office loads were often included in the energy use reported by Valco et al. (2009). The monitored power factor was within the range (0.74-0.86) reported by Wilmot and Alberson (1964b). This result indicated that some

Table 3. Electricity use and power factor.

Gin	# Bales	kWh Bale ⁻¹	Power Factor
A	16774	31.5	0.753
B	26899	40.5	0.789
C	5968	27.7	0.830
D	25626	43.5	–
Total/Mean	75262	35.8	0.791

motors in the monitored gins were oversized, since power factor at full load for the motor sizes found in cotton gins is typically 0.80-0.85 (NEMA, 2007).

The distribution of electricity use by gin function is shown in table 4. This allocation of electrical energy use was similar to the distribution reported by Funk and Hardin (2011). Electricity use in all categories varied greatly between gins, primarily because of differences in machinery used. Gin A required the least energy per bale for both seed cotton and lint cleaning. This gin had fewer installed cleaning machines and bypassed the stick machine and second stage lint cleaner during the monitoring period. Energy used for ginning was the least variable, with gin B using significantly more energy due to excess installed ginning capacity. Bale packaging energy differed considerably between gins; however, this research did not identify an explanation. Material handling varied according to the layout of the gin plant. Gin C used conveyors for trash handling instead of fans, significantly reducing energy requirements. Conversely, gin D had an additional stage of drying, requiring additional fans.

The average power required for different gin functions, while running at maximum capacity and idling, is shown in table 5. Idling required 71% of the power used at maximum capacity. Ginning used a significant amount of power at maximum capacity; however, only 29% of the maximum power demand was required when idling. Seed cotton cleaning and lint cleaning required 59% and 64%, respectively, of the maximum power at idle. While the power used by bale packaging equipment varied significantly between gins, the proportion of the maximum power demand used at idle did not vary as much and averaged 69%. Most energy used for bale packaging was consumed by the motors driving large hydraulic pumps for the press ram and tramper. Even when operating at maximum capacity, significant energy is used when cotton is not being compressed by the hydraulic cylinders. Between compression strokes, the hydraulic fluid is still pumped through lines and valves. Consequently, if the processing rate slows or the gin is idled, the average power consumed by the bale packaging equipment does not decrease much from the average power used at the maximum processing rate. Gins have operated press ram pump motors intermittently; however, this technique usually does not allow adequate rest time for motor cooling

Table 4. Distribution of electricity use by gin process.

Gin	Seed Cotton Cleaning		Ginning		Lint Cleaning		Bale Packaging		Material Handling	
	kWh Bale ⁻¹	%	kWh Bale ⁻¹	%	kWh Bale ⁻¹	%	kWh Bale ⁻¹	%	kWh Bale ⁻¹	%
A	1.3	4.1	5.5	17.5	1.2	3.8	5.2	16.5	18.3	58.1
B	4.0	9.9	8.6	21.2	2.5	6.1	4.6	11.4	20.8	51.4
C	2.2	8.0	6.2	22.3	2.4	8.5	2.5	9.1	14.4	52.1
D	4.0	9.2	5.3	12.1	3.6	8.2	2.9	6.7	27.8	63.8
Mean	2.9	7.8	6.4	18.3	2.4	6.7	4.4	10.9	20.3	56.4

Table 5. Power used by different gin functions.

Gin		Seed Cotton Cleaning	Ginning	Lint Cleaning	Bale Packaging	Material Handling	Total
A	Idle (kW)	21	44	22	133	536	756
	Running (kW)	47	206	43	176	625	1097
	Idle/Running (%)	45	21	51	76	86	69
B	Idle (kW)	83	125	53	104	623	988
	Running (kW)	139	319	87	156	670	1371
	Idle/Running (%)	60	39	61	67	93	72
C	Idle (kW)	52	66	62	71	437	689
	Running (kW)	88	248	92	99	552	1080
	Idle/Running (%)	59	27	67	72	79	64
D	Idle (kW)	74	45	72	49	657	898
	Running (kW)	106	158	94	79	708	1145
	Idle/Running (%)	70	28	77	62	93	78

between starts, shortening motor life (NEMA, 2007). Material handling motors used 88% of the maximum power demand at idle, primarily due to the increased power required by unloaded centrifugal fans used for pneumatic conveying. By eliminating fans, gin C required the least power for material handling and also had the lowest proportion of maximum demand for material handling used at idle.

The gin stand operating efficiency, the proportion of time each gin stand motor was on that was actually spent ginning cotton, is shown in table 6. Gin stands were numbered in the direction of movement of cotton by the distributor conveyor, so that the first stand was farthest from the overflow. The mean operating efficiency for all gins was 91.65%, greater than the 84.2% reported by Watson and Holder (1964). This increase was likely due to improvements in technology, particularly the replacement of trailers with modules, which allowed more consistent feeding of cotton into the gin plant and improved feed control technology. At all gins, the least efficient stand was the final stand before the overflow, indicating that occasionally more cotton needed to be fed into the gin to keep the final stand fully loaded.

The final stand was only 1.5% to 2.0% less efficient than the other stands, except at gin D. Further compounding this problem, the third stand at gin D often operated at less than full capacity. A frequency distribution of gin stand current (fig. 2) illustrates this situation.

A common concern for gin managers is determining if the gin should be shut down or left idling for minor maintenance or repair. The median energy used and times required to start the gins are shown in table 7. Median values were used because the data was significantly skewed. For all gins, the average power required during startup was less than the power used at idle; consequently, if only electricity use was considered, the breakeven idling time would be less than the startup time. Despite greater power required over several seconds when starting a motor, the average power for the entire gin is less during startup because motors are turned on sequentially. However, the time required to start the gin has a significant impact on

Table 6. Gin stand operating efficiency.

Gin	Stand #1 (%)	Stand #2 (%)	Stand #3 (%)	Mean (%)
A	95.00	93.25	–	94.13
B	90.26	90.86	88.88	90.00
C	96.15	94.68	–	95.42
D	91.54	91.66	77.95	87.05

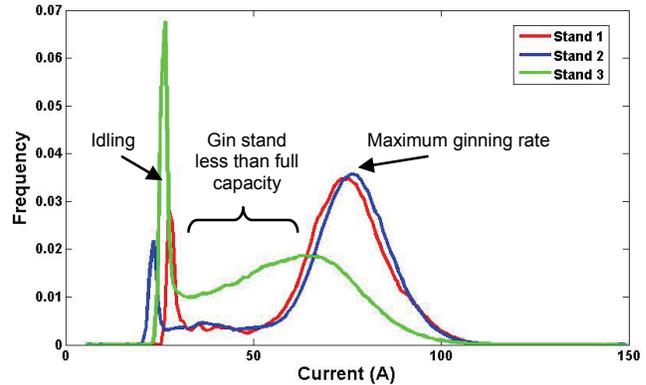


Figure 2. Distribution of gin stand current at gin D.

Table 7. Energy and time required to start gins and estimated breakeven idling time.

Gin	Energy (kWh)	Startup Time (s)	Breakeven Idling Time (s)
A	23.6	185	553
B	19.6	197.5	455
C	41.2	260	891
D	68.7	370	993
Mean	38.3	253.1	723.0

cost. Estimates for gins' hourly labor cost (\$162 h⁻¹) and electricity cost (\$0.093 kWh⁻¹) were obtained from surveys (unpublished data, T.D. Valco, USDA-ARS) and used in equation 1 to calculate the breakeven idling times in table 7.

Watson and Looney (1964) reported a breakeven idling time of only 1.25 min. However, their analysis only considered the idling power and energy required to start each motor individually (not the energy used by the entire gin plant during its normal starting sequence) and allowed an additional 1 min for stopping and restarting. The incorporation of labor costs for the additional time required to stop and restart would likely result in an estimate closer to the average value of 12 min reported in table 7.

Gins' costs, particularly for labor, will vary significantly. Furthermore, the starting times shown in table 7 were typically after scheduled cleaning and maintenance, when all cotton was processed through the gin before equipment was turned off. During an unplanned shutdown and restart of machinery, the time required may differ. While 12 min can be used as an initial estimate, gin managers should determine appropriate parameters to use in equation 1 for their gin to calculate a breakeven idling time.

Table 8. R² values for total and component power and power factor.

Gin	Total	Seed Cotton Cleaning	Ginning	Lint Cleaning	Bale Packaging	Material Handling	Power Factor
A	0.698	0.582	0.645	0.593	0.137	0.622	0.663
B	0.721	0.508	0.626	0.689	0.137	0.706	0.591
C	0.557	0.391	0.460	0.961	0.304	0.351	0.531
D	0.301	0.174	0.651	0.158	0.374	0.122	–

MODELING

R² values from fitting equation 4 to the power data are shown in table 8. At gins A and B, values were between 0.508 and 0.721, except for the model for bale packaging power. A wide variation was observed in the power required for bale packaging near the maximum processing rate. Because the datalogger was not capable of sampling data faster, the maximum power required by the bale press when compressing a bale may not have always been recorded. Although the compression of a bale only required a short time, this event accounted for a significant portion of the bale packaging power. Bale moisture may also have varied, which would affect the force required to compress a bale (Anthony and McCaskill, 1976). R² values were lower for total, seed cotton cleaning, ginning, and material handling power and power factor at gin C because most monitored bales were produced near the maximum ginning rate; therefore, less of the variation in the data was explained by the model. Lint cleaning power was the exception at gin C, as most variation in the data was accounted for by the number of stages of lint cleaning used.

At gin D, data was only sampled every 5 s; consequently, the measurement error was higher and the R² values for total, seed cotton cleaning, and lint cleaning power were lower. Estimating power factor at gin D also was an additional source of error in modeling power data. The material handling power R² was nearly zero at gin D. This is a result of both the higher measurement error and the similar power used for material handling at both idle and maximum capacity (table 5).

A plot of the model (predicted values calculated using the mean gin temperature) and actual total power data at gin A are shown in figure 3. The model parameters for total power are listed in table 9. The temperature coefficient was more negative at gins B and D, where temperature was measured in the gin building, than at gins A and C where temperature data was acquired from an outdoor weather station. This difference likely occurred because temperature in the gin building will vary less than the outdoor temperature. The large difference in the stages of lint cleaning coefficient between gins B and C was due to the fan arrangement at the two gins. Separate fans were used on the first and second stage lint cleaner condensers at gin B, while gin C utilized a common fan for both stages. Consequently, gin C could not turn fans off when using a single stage of lint cleaning, and the energy savings were smaller.

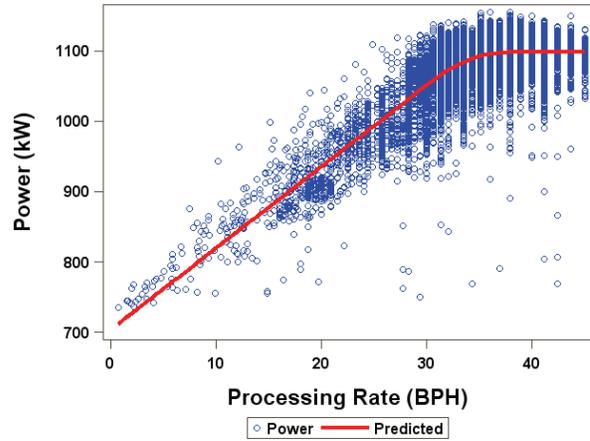


Figure 3. Power and processing rate at gin A.

Similar results were observed for modeling component power and power factor. A plot of the power factor model and actual power factor data for gin A are shown in figure 4. This model has an intercept of 0.668 (power factor at idle), linear region slope of 0.00275, and maximum value of 0.761. The temperature coefficient was -0.00019°C⁻¹ (predicted values shown in fig. 4 were calculated at the mean gin temperature).

Using the parameters in table 9 for gin A, the predicted and actual electrical energy (at mean gin temperature) used per bale is shown in figure 5. The model accounted for more than 97% of the variation in total electrical energy use per bale at each gin because of the significant effect of

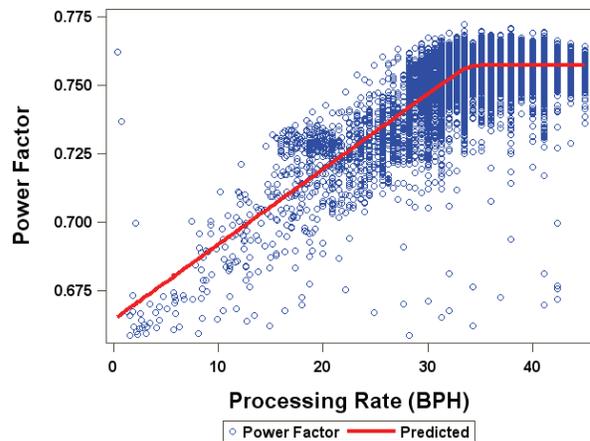


Figure 4. Power factor and processing rate at gin A.

Table 9. Model parameters for total power.

Gin	a ₁ (P _{idle})	a ₂ ((P _{max} - P _{idle})/R _{max})	a ₃ (temperature coefficient)	a ₄ (stages of lint cleaning coefficient)	a ₇ (P _{max})	R ₁	R ₂
A	717	11.59	-0.68	–	1111	30.34	37.78
B	879	12.00	-2.57	79.41	1334	33.94	41.80
C	629	13.10	-1.77	31.23	1078	29.69	38.88
D	1017	5.39	-2.33	–	1179	29.03	31.27

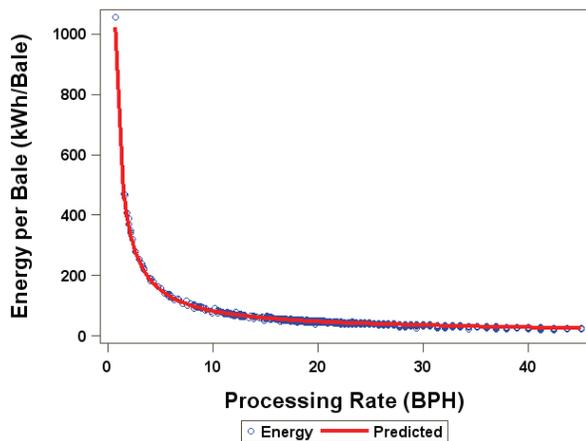


Figure 5. Electrical energy per bale and processing rate at gin A.

processing rate on electricity use. This result indicates the importance of gin management practices that maximize processing rate in reducing energy use. Downtime (with motors left on) should be minimized and all equipment should be operated at capacity as often as possible.

CULTIVAR AND CLASSING DATA

All independent variables and covariates were significant effects in the mixed models for electrical energy use per bale, processing rate, and average power demand for each bale. Table 10 shows the least squares means for cultivars with greater than 300 monitored bales. The energy use varied significantly between cultivars, primarily due to differences in processing rate. While significant differences were noted in the power required for each cultivar, these differences were not practically significant. The difference in energy use between the lowest demand (1053 kW) and the highest (1064 kW) at 40 bales h⁻¹ is less than 0.3 kWh bale⁻¹. This result was expected because the gin stand feed controls at gin C were designed to maintain constant amperage on the gin stand motor.

The total ginning energy for the different cultivars shown in table 10 was significantly less than the ginning energy determined by Anthony (1989). The idling power required by the 20-saw gin stand used by Anthony is likely a much higher percentage of the maximum power demand while ginning. However, the net ginning energy for all cultivars is near the mean (20.2 Wh kg⁻¹) calculated by Boykin (2007).

For a specific cultivar and level of lint cleaning, USDA-AMS classing data was not correlated with average power demand, processing rate, or electrical energy use per bale. With two stages of lint cleaning (most bales), the absolute value of all correlation coefficients was less than 0.2. No significant correlation was observed when data from all

cultivars was analyzed together, indicating that differences in processing rate and energy use between cultivars could not be explained by the differences in the classing data between cultivars.

CONCLUSION

The gins monitored in this study were more efficient than past surveys indicated, with a mean electricity use of 35.8 kWh bale⁻¹. A wide variation in average electrical energy use existed between gins, with a range of 27.7 to 43.5 kWh bale⁻¹. This variation was primarily due to differences in installed equipment and layout. Replacing fans with mechanical conveyors can result in significant electricity savings. Bypassing unnecessary cleaning equipment can also reduce electricity use. While some cleaning is necessary to produce acceptable grades, the required level of cleaning is variable and depends on cultivar, weather, and harvesting practices.

Average power factor was 0.791, indicating that some motors were not operating near full load. The distribution of energy use by gin function was similar to previous research, with material handling accounting for over 56% of electrical energy use. Gins required 71% of the maximum power demand when idle; consequently, gin managers should minimize downtime. The breakeven idling time was estimated to be between 7.6 and 16.6 min at the monitored gins, considering the extra time and labor cost involved in restarting the gin. Gin stands operated at 92% efficiency, higher than previously reported. However, the last stand was found to be less efficient and often operated at less than full capacity. Operating all equipment at capacity as much as possible is necessary for maximum energy efficiency.

A model was developed to predict power demand based on processing rate, gin temperature, and stages of lint cleaning used for each gin. R² values for the model were between 0.301 and 0.721 for the gins, with an average of 0.569. Using the parameters from this model, nearly all variation in electrical energy use per bale was explained. One gin provided cultivar and classing data for monitored bales. Cultivar was found to have a significant effect on electricity use per bale, primarily due to differences in processing rate of different cultivars. No correlation was found between classing data and electricity use per bale, power demand, or processing rate.

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Table 10. Least squares means of different cultivars at gin C for energy use, processing rate, and power.

Cultivar	No. Bales	Energy (kWh bale ⁻¹) ^[a]	Processing Rate (bales h ⁻¹)	Power (kW)	Total Ginning Energy (Wh kg ⁻¹)	Net Ginning Energy (Wh kg ⁻¹)
FM 1740 B2R	392	25.5a	42.1a	1053a	26.3a	19.3a
DG 2570 B2RF	1153	26.0b	41.3b	1056a	26.9b	19.7b
PHY 375 WR	1895	26.2c	41.1c	1061b	27.0b	19.8b
ST 4498 B2R	321	26.9d	39.9d	1064b	27.8c	20.5c

^[a] Means in a column followed by the same letter are not significantly different at the 5% level.

provided survey data and other input to enhance this research.

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NOMENCLATURE

$a_1...a_7$	parameters in power model
$C_{electricity}$	electricity cost (\$ kWh ⁻¹)
$C_{variable\ labor}$	variable labor cost (\$ h ⁻¹)
E	electricity used per bale (kWh bale ⁻¹)
$E_{starting}$	electricity used while starting gin (kWh)
LC	indicator variable for stages of lint cleaning used
P	gin power demand (kW)
P_{idle}	gin power demand while idling (kW)
P_{max}	gin power demand at maximum processing rate (kW)
R	gin processing rate (bales h ⁻¹)
R_1	processing rate where linear region ends in piecewise power model (bales h ⁻¹)
R_2	processing rate where plateau region begin in piecewise power model (bales h ⁻¹)
R_{max}	maximum gin processing rate (bales h ⁻¹)
T	gin temperature (°C)
$t_{breakeven}$	breakeven idling time, where cost of idling equals cost of stopping and restarting gin (s)
$t_{starting}$	time required to start gin (s)