The Relationship between Manufacturing Efficiency and Energy Productivity

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ABSTRACT

The relationship between manufacturing efficiency and energy productivity is poorly understood (Papadaratsakis, 2007). Most manufacturers assume that increasing productivity means increasing energy usage at about the same energy intensity (EI) level. Others believe there is a volume effect with increased production and EI goes down only to discover that it rises. This paper will investigate the relationship between these components using a model presented at the 2009 ACEEE conference to measure energy savings through process improvements in manufacturing plants (La Palme, 2007). The model offers energy efficiency calculations for whole building, prescriptive measures, or regression analysis. Five examples of varying operating conditions will be presented from a thermoforming plant in Southern California. The first is the baseline model. The second will show changes in energy intensity when there is a decrease in manufacturing output with no increase in production time. The third will analyze the same plant with an increase in manufacturing output with a similar increase in production time. The fourth example will demonstrate variation in product demand. This example creates great EI measurement difficulties and is common to all plants. The fifth will be an increase in output with no increase in production time through improvements in manufacturing efficiency based on system optimization (Church, 2005). Changes in manufacturing operations alter energy intensity and how these affect energy productivity will be analyzed. Finally, what tradeoffs should plants consider planning on certifying under the soon-to-be-released ISO 50001 taking the Plant Energy Intensity pathway?[1]

Introduction

There is currently a growing need for manufacturing plants to improve competitiveness by reducing costs in all categories. These same plants also desire to sell more. Two strategic initiatives can support these objectives. First, reducing costs by eliminating waste in all forms and improving product quality. Second, certifying under the impending international standard for energy management, ISO 50001, will provide competitive advantage through product labeling with the expectation of driving increased sales. This paper will focus specifically on analyzing energy waste and how it is impacted with changes in product demand.

[1] See Superior Energy Performance for ISO 50001 certification criteria: http://superiorenergyperformance.net/index.html

Baseline Model

All models were created from a plastics thermoforming plant operating under nearly identical conditions. To simplify the analysis even further variables were constrained to the following attributes using a ten week period.

Assumptions for the baseline model:

1. An injection molding plant with 11 machines running 6000 hours per year, three machines, 8,9, and 10 running 7200 hours year to meet customer demand for one dedicated product line, and a shredder and extruder running 6500 hours per year (see Appendices A and B for direct and indirect energy consumption for the plant).
2. Production hours run three shifts Monday-Friday for all machines with 2-3 Saturdays per month and an occasional Sunday all running three shifts for machines 8, 9, and 10.
3. Machine uptime is poor due to six hour changeovers and other machine downtime.
4. Product yield is poor at 88% with 10% cutting scrap loss.
5. Set-up changeover time equals 6 hours/machine.
6. A shredder and extruder run two shifts Mon-Fri. year round with some weekends.
7. Baseline energy intensity equals 1.87 Lbs. per kilowatt consumed.

Table 1. Daily Plant Production Log Example

Machine/Process		Y		X2	X3	X4	X5
Units							
Day	Date	kWh/day	kWh/material	Material	Day Type	Weighted Ave	Weekday
1	03/07/08	21485.7	3.3177	6476	wkdy	0.0311	1
2	03/21/08	21444.7	2.5032	8567	wkdy	0.0311	1
3	03/28/08	21065.5	2.2097	9533.1	wkdy	0.0305	1

Table 1 above is a sample daily log for collecting production data. Figure 1 below is the daily energy intensity for the plant summed over a ten week period. This performance is very similar to approximately 50 manufacturing plants the author's studied over a three year pilot utility program. The large swings in energy intensity were often related to large variance in product output, production hour changes, product quality, and when there was a high ratio of support energy to direct energy. For this plant, the large weekend energy intensity increase came from running only 20% production equipment with 100% support energy.

Figure 1. Kilowatt Hours Per Pound of Material Processed

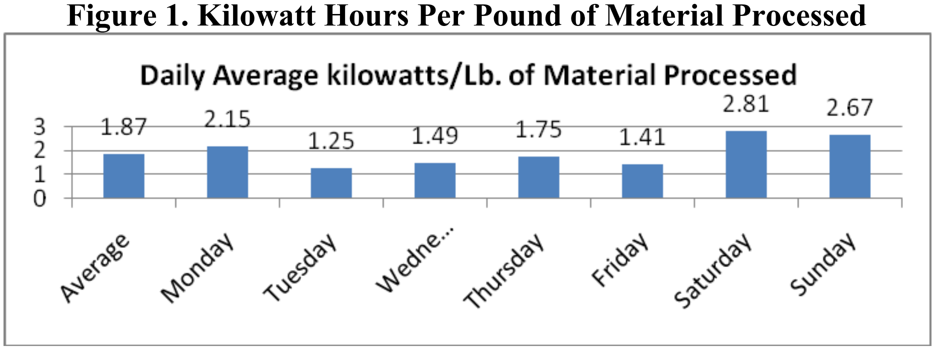


Figure 2 is a regression analysis showing energy consumed per one pound of raw material thermoformed. While there is not sufficient room to plot all the coordinate values, the upper left hand is where energy productivity is at its worst. These points are predominately Saturday and Sunday production days. It was common for manufacturing plants to have extensive data on production output and other fixed costs such as labor, but rarely did they understand their fluctuating energy costs.

Figure 2. Regression Analysis Showing Energy Intensity Performance

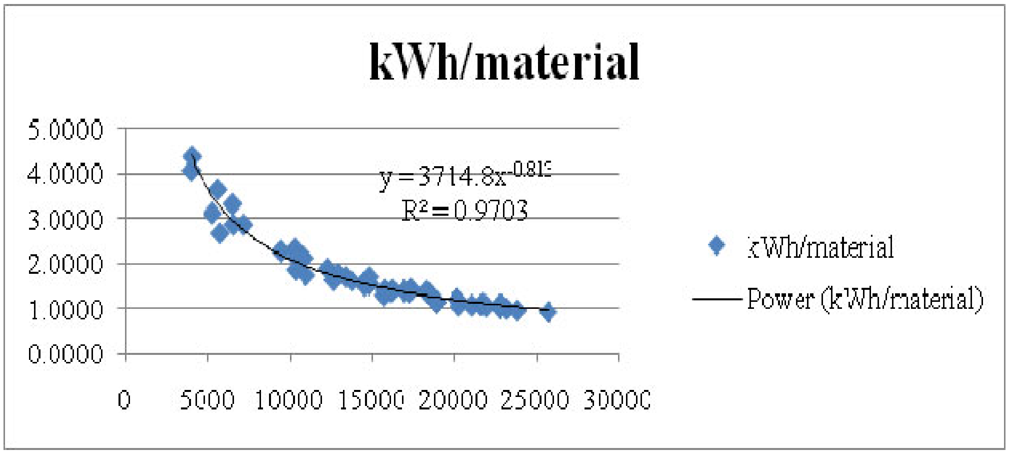
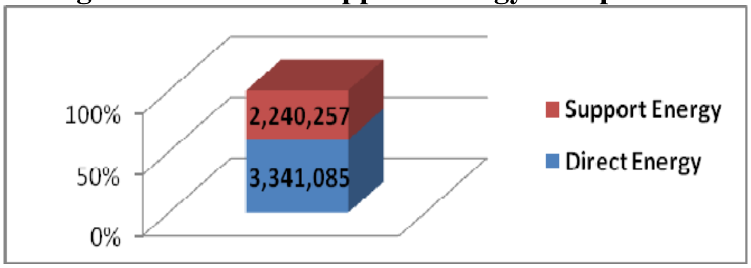


Figure 3 represents annual kWh consumption between direct and indirect energy usage. While the average ratio is roughly 60:40 for weekday shifts, the ratio flips over and becomes 25:75 direct to indirect energy consumed on weekends for the plant.

Figure 3. Direct to Support Energy Comparison



Model 2: 10% Decrease in Product Demand

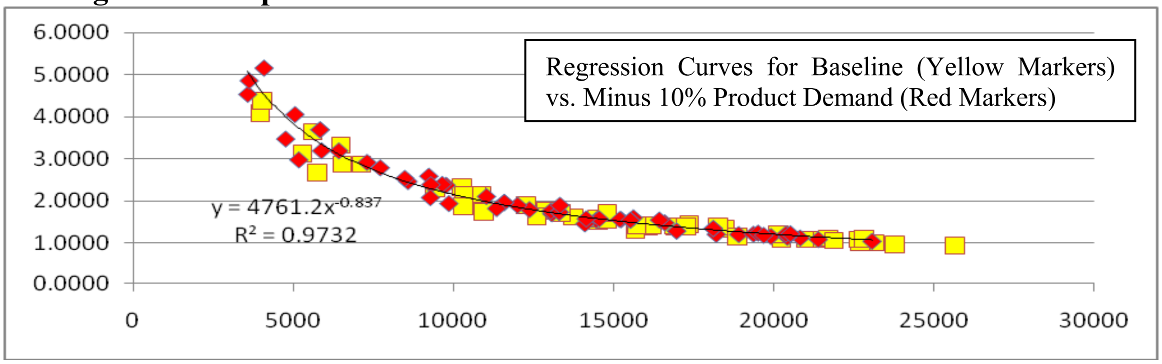
Assumptions for the second model:

1. A decrease of 10% in manufacturing output for products not produced by machines 8, 9, and 10. They continue to run the same hours including weekends.
2. Yield, material scrap, and machine utilization remain the same.
3. Support energy continues to run 100% on weekends.

The expectation for the plant's energy intensity under this model is straight forward. It can be easily predicted energy intensity will rise from the baseline model without the ability to reduce support energy usage to match declining demand. This is seen in the regression analysis as a flatter extended curve moving from left to bottom right for the baseline model in Figure 4. As the points move towards the upper left hand quadrant energy intensity or energy productivity is poorer. The product demand reduction model is even less effective than the baseline.

A number of simple actions such as adding automation and controls, reducing plug-load, shifting production, and reducing operating hours by improving manufacturing efficiency would improve energy intensity substantially. The energy intensity is demonstrated in Figure 7 with a reduction in demand exhibiting slightly poorer energy productivity than the baseline model.

Figure 4. Comparison between Baseline and -10% Product Demand Models



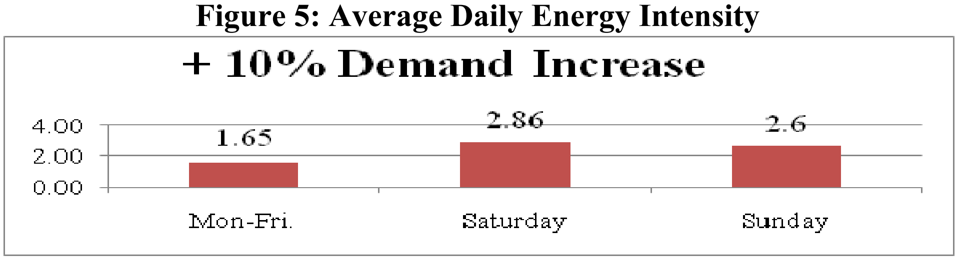
Model 3: 10% Increase in Product Demand

Assumptions for the third model:

1. Increase in manufacturing output 10% with same increase in operating hours
2. Manufacturing output is increased by adding a single shift operating 2 Saturdays per month
3. Yield, scrap, and machine utilization remain the same
4. Support energy continues to run 100% on weekends.

This model is more intriguing than the last one. There is a general view that energy intensity should go down and energy productivity go up when demand increases. The so-called volume effect does not materialize in this model. Since the plant is already running three shifts throughout the week the only the only time period to increase production is on the weekends, which is already the worst energy intensity period. The following shows the relationship the plant encounters on weekends.

Figure 5: Average Daily Energy Intensity



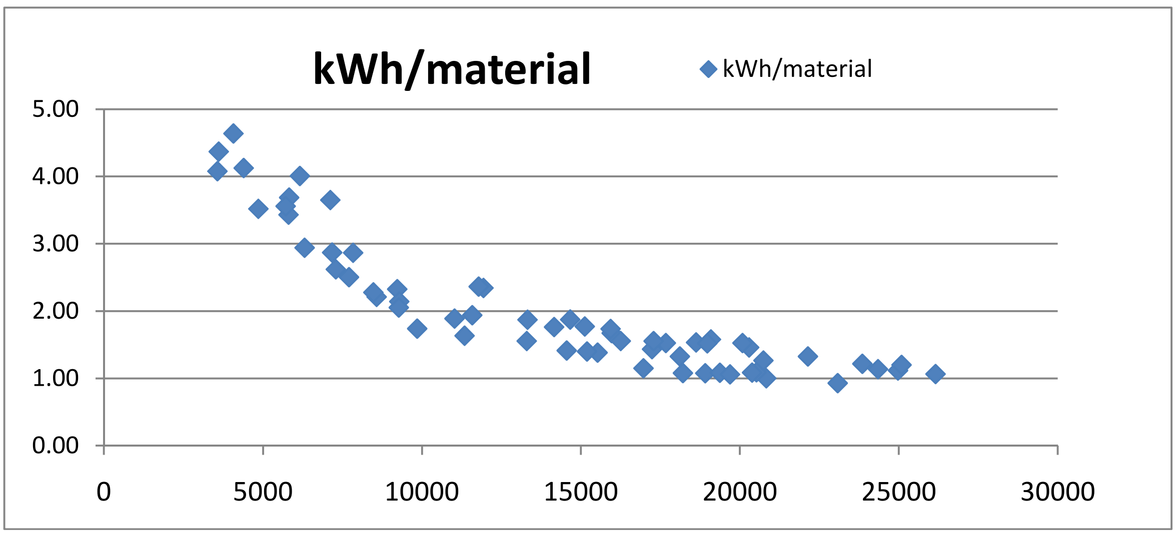
Model 4: Product Demand Fluctuating Plus and Minus 10% Every Five Days

Assumptions for the fourth model:

1. Variable production of plus and minus 10% alternating every 5 days
2. Yield, scrap rate, and machine utilization remain the same
3. Support energy continues to run 100% on weekends.

This model evaluates demand variation, which should not be confused with product shifting variation. Demand variation and its role effecting energy productivity is fairly simple to demonstrate when the raw material is the same feedstock used plant wide. Examples include food, cement, glass, plastics, and chemical processes. Product demand variation is much more difficult to measure with respect to energy intensity especially when it's coupled with product variation. Figure 6 below shows the greatest amount of energy intensity variation of any of the models studied from this variation in customer demand. It was not within the scope of this paper to analyze other demand related variations affecting the manufacturing system including product shifting but these pose significant energy intensity measurement difficulties.

Figure 6: +/- Demand Variation Every 5 Days Showing Energy Intensity Separation



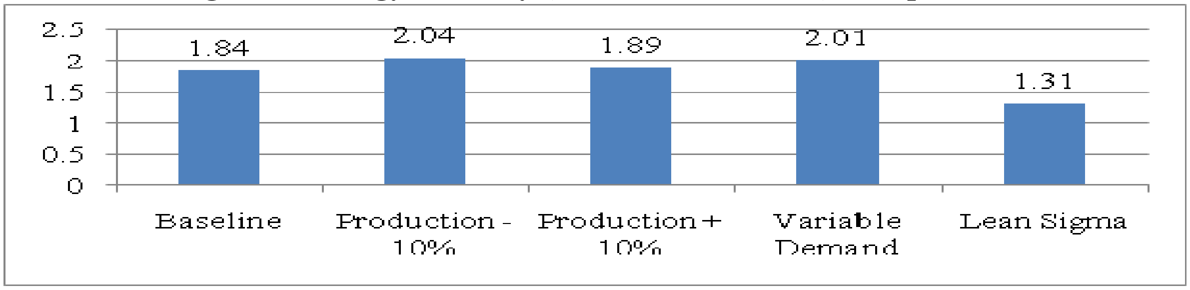
Model 5: Same Product Demand as Baseline Model with Lean/Sigma Improvements

Assumptions for the fifth model:

1. This model is based on the same demand as the baseline model.
2. Process improvements were made including reduction in machine set-up times from eight to two hours, cutting scrap reduction to an industry standard of 2%.
3. No energy efficient equipment changes were made at this point. However, these can often lead to improvements in the manufacturing system and improve return on investment (Church, 2009).
4. Improved production scheduling to smooth out demand variation.

5. Changes made to the manufacturing system to reduce energy intensity and improve energy productivity are summarized in Appendix C.
6. Support energy does not run on weekends due to improved manufacturing system optimization.

Figure 7. Energy Intensity (kWh/lb. of material) Comparison



Lean Sigma deployment targeting machine changeovers and scrap reduction was applied to the baseline data demonstrating substantial reduction in energy intensity (Figure 7). While not run against the variable demand data set, it is predictable it will outperform the 2.01 kWh/lb. results. Because Lean/Sigma is fundamentally based on system optimization principles, it is capable of responding best to every type of demand model demonstrated. In addition, due to its responsiveness to rapid changes in demand fluctuations, Lean/Sigma can also manage product variations with the least amount of energy waste.

In figure 8 below we can see how energy waste is distributed with many more high energy intensity days in the upper left hand corner and fewer days in the 1.0 to 1.25 kWh per pound of material processed.

Figure 8. Energy Intensity Difference between High Demand Variation and Lean/Sigma

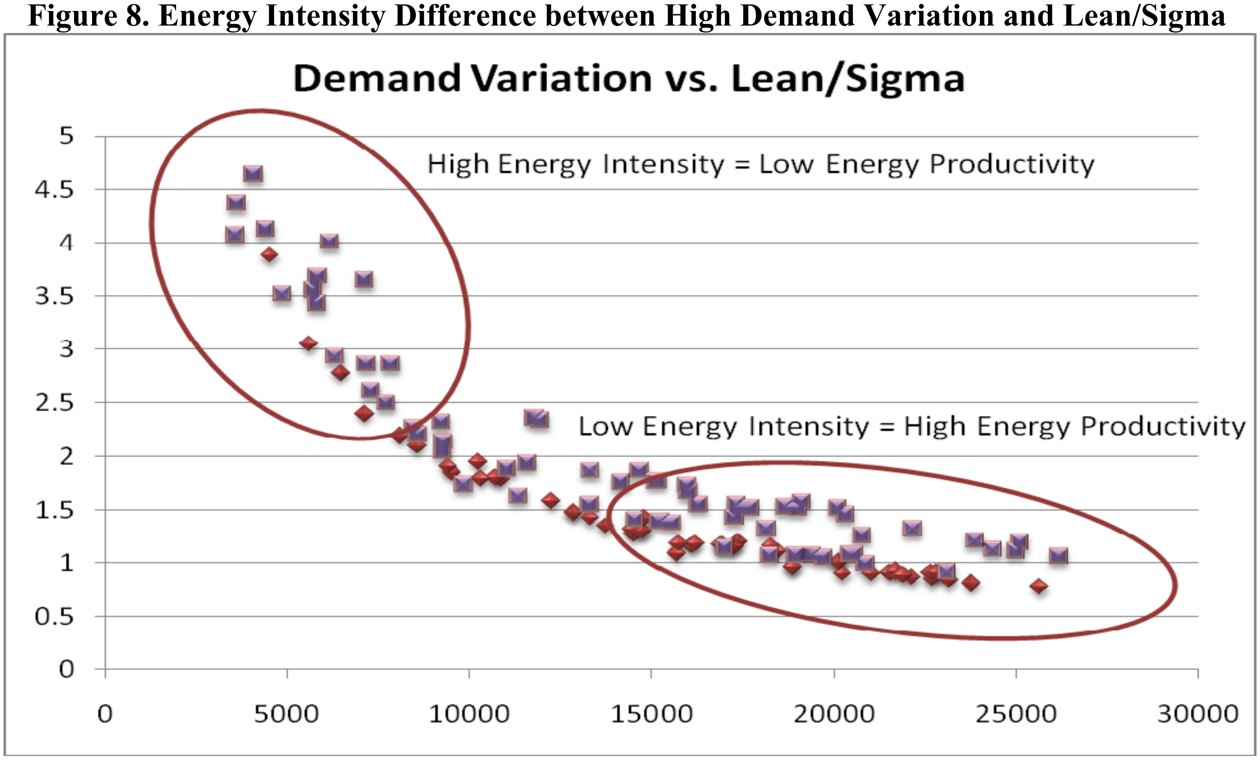


Table 2 below shows annual energy savings against the baseline model. The results range from approximately a 10% annual energy increase to a reduction of 30% from the baseline. Energy intensity per pound of material thermoformed ranges from 1.31 to 2.04. There was an additional 322,905 annual kWh hardware savings found in the plant shown in Appendix C.

Table 2. Energy Savings Comparisons between the Five Demonstrated Models

Modeling Results	Baseline Performance	Baseline - 10%	Baseline + 10%	Variable Demand	Lean/Sigma
Lbs. of Material	861,893	861,893	861,893	861,893	861,893
kWh/Lb. Material	1.84	2.04	1.89	2.01	1.31
Total kWh/10 weeks	1,585,883	1,758,262	1,628,978	1,732,405	1,129,080
Annual kWh	6,343,532	7,033,046	6,515,911	6,929,619	4,516,319
Annual kWh saved	Baseline	(689,514)	(172,379)	(586,087)	1,827,213

Findings

A baseline production efficiency model was designed from a plastic manufacturing plant studied for eighteen months in Southern California. A ten week period was selected for analysis as the most representative time period for the plant. Small adjustments were made to reduce variables. Four models were then adjusted and compared to the baseline model and against each other.

Observed results were somewhat predictable while several were not. The first model studied, Baseline Minus 10% Product Demand, showed an increase of 689,514 annual kWh over the baseline model amounting to an 11.5% increase. The second model, Baseline Plus 10% Demand, expected to have a lower kWh per unit of output, was slightly higher than the baseline model in energy intensity. The third model, Variable Demand shifting every five days, performed at just about at the same level as the -10% Demand Reduction model or close to the poorest performance. The last model tested, Lean/Sigma resolved system inefficiencies and was by far the best in reducing energy intensity.

Based on the author's experience and observations, while the Lean/Sigma results are impressive and similar results achievable in most manufacturing plants, a word of caution regarding implementing the changes is in order. In most cases, Lean/Sigma deployment is targeted at changing behavior that is often rooted in the manufacturing system. Adjusting the manufacturing system requires discipline and support from senior management if the changes are to be sustained. Due to this dynamic, the initial projects need to be selected based on reduced risk for generating positive results above targeting the largest energy savings projects with highest failure prospects. Finally, there are often energy efficiency equipment retrofits that will contribute both to energy savings and improvements in energy productivity. These projects should be located and implemented early in a plant's efforts to reduce energy intensity and improve energy productivity.

References

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Church, G., LaPalme G., and Stevens, G. 2009. "Energy Project Financial Analysis: What Have We Been Missing? *In Proceeding of the ACEEE Summer Study on Energy Efficiency in Industry* Washington D.C.: American Council for an Energy-Efficient Economy.

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Appendix A: Direct Energy Equipment

Form-1, Process Description:							
Step	**Description**	**Connected Electrical Load**	**Load Factor (0-1)**	**Utilization Factor (0-1)**	**Hr/Yr**	**Estimated kWh**	**% Energy Intensity**
1.01	Machine-1, Sencorp, M/N 2500, 460V/3PH/60Hz/225FLA	152.38	0.60	0.40	6,000	219,423	6.57%
1.02	Machine-2, Sencorp, M/N 2500, 460V/3PH/60Hz/225FLA	152.38	0.60	0.40	6,000	219,423	6.57%
1.03	Machine-3, Sencorp, M/N 2500, 460V/3PH/60Hz/225FLA	152.38	0.60	0.40	6,000	219,423	6.57%
1.04	Machine-4, Sencorp, M/N 2500, 460V/3PH/60Hz/225FLA	152.38	0.60	0.40	6,000	219,423	6.57%
1.05	Machine-5, Sencorp, M/N 2500, 460V/3PH/60Hz/230FLA	152.38	0.60	0.40	6,000	219,423	6.57%
1.06	Machine-6, Sencorp, M/N 2500, 460V/3PH/60Hz/258FLA	152.38	0.60	0.40	6,000	219,423	6.57%
1.07	Machine-7, Sencorp, M/N 2500, 460V/3PH/60Hz/258FLA	152.38	0.60	0.40	7,200	263,308	7.88%
1.08	Machine-8, Sencorp, M/N 2500, 460V/3PH/60Hz/258FLA	152.38	0.60	0.40	7,200	263,308	7.88%
1.09	Machine-9, Sencorp, M/N 2500, 460V/3PH/60Hz/258FLA	152.38	0.60	0.40	7,200	263,308	7.88%
1.1	Machine-10, Sencorp, M/N 2500, 460V/3PH/60Hz/258FLA	152.38	0.60	0.40	6,000	219,423	6.57%
2.01	Contract Packaging (6 machines), typ. Cosmos Electric, M/N F10-25, 10 kW @ 27.1 MHzNom., 220V/60Hz/3PH/48 A.	60.00	0.20	0.80	6,000	57,600	1.72%
3.01	Quidel Assembly Room [10 kW assumed]	10.00	0.20	0.60	6,000	7,200	0.22%
4.01	AMD & WD Assembly Room [10 kW assumed]	10.00	0.20	0.60	6,000	7,200	0.22%
5.01	Tool & Dye Area [10 kW assumed]	10.00	0.20	0.60	6,000	7,200	0.22%
6.01	Recycling Extruder [equipment specs to be provided, currently assuming 100 kW based on preliminary site data]	100.00	0.60	0.80	6,500	312,000	9.34%
6.02	Recycling Shredder [equipment specs to be provided, currently assuming 200 kW based on preliminary site data]	200.00	0.60	0.80	6,500	624,000	18.68%
Total						**3,341,085**	**100.00%**

Appendix B: Support Energy Equipment

End-use	Description	Connected Electrical Load	Utilization Factor (0-1)	Load Factor (0-1)	Hr/Yr	Est. kWh Usage
Office Lighting	The office lighting assumptions are 2.5 Watts/ft2 and 10,000 ft2 of office space.	25.0	1.00	1.00	2,500	62,500
High Bay Lighting	The baseline fixtures were MH400/1. The high bay lighting was recently upgraded. Until the lighting equipment survey is received, the high bay lighting assumptions are 1.0 Watts/ft2 and 157,200 ft2 of office space.	157.2	1.00	1.00	6,600	1,037,520
Exterior Lighting	6-MH1000/1 @ 1080 Watts/Fixture 1.0 Watts/ft2 and 157,200 ft2 of office space.	6.5	1.00	1.00	4,380	28,382
Space Cooling	The space cooling load assumes the following 400 ft2/ton, 10,000 ft2, 10.5 EER (or 1.15 kW/ton) and 1,500 full load hours.	28.8	1.00	1.00	1,500	43,125
Processing Cooling	Carrier, M/N 30GXN114-A-661FQ.	142.5	1.00	0.60	3,000	256,500
Compressed Air System	Lead compressor is Kaeser DSD 150 (total hours 18762; total load 7112). Lag compressor is IR SSR-EP100.	235.0	0.80	0.60	7,200	812,229
Total						**2,240,257**

Appendix C: Energy Savings Calculator

Energy Savings Analysis

Utility Bill Total (previous year)	kWh/yr
Monthly utility bill data from 5/14/08 to 4/15/08	4,687,799
Interval utility bill data from 3/1/08 to 6/31/08	7,502,406

Utility Bill Analysis Baseline Energy Consumptions	kWh/yr
Pre-Installation Energy Consumption	6,417,941

Stipulated Baseline Energy Consumptions	*kWh/yr*
Estimated Process Energy Consumption (Form-1) is	3,341,085
The associated ancillary load (Form-5) is	2,240,257
Based on the stipulated calculations, the total energy consumption is	5,581,342

Calculated Energy Savings

Measures	Option-A kWh/yr	Option-C kWh/yr	Selected Option	Savings kWh/yr
Waste Minimization Improvement(s)	0	64,179	○A ◉C	64,179
Efficiency Improvement(s)	0	0	○A ○C	0
Productivity Improvement(s)	422,565	686,812	◉A ○C	422,565
Total				486,745

Potential Energy Efficiency Opportunities

EEM	CAT.	Description	kW	kWh/yr
1	L	The high bay lighting was completed on MM/DD/YR. The lighting contractor estimated the reported savings.	TBD	TBD
2	L	Exterior CFL replacements.	TBD	TBD
3	O	Compressor Leak Detection and Repair	0.0	81,223
4	O	Compressor VSD Control	0.0	219,302
5	O	Chiller Water Pump VSD Control	0	22,380
Total				322,905

Footnotes: