Lean Energy Analysis: Guiding Industrial Energy Reduction Efforts to the Theoretical Minimum Energy Use

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ABSTRACT

Industrial energy use is heavily reliant on electricity and fuel from non-renewable sources. Most analyses expect global oil and natural gas production to decline within the next 30 years, while an expanding world population and economy will demand ever-increasing amounts of energy. This discrepancy will invariably increase energy prices and threaten economic development. As such, increasingly dramatic industrial energy efficiency improvements will be needed to maintain the economic viability of manufacturing companies and entire economies. Governmental organizations such as the US Department of Energy (DOE) and the United Nations Development Programme (UNDP) have bracketed energy efficiency potential by calculating the theoretical minimum energy use of some energy-intensive industrial processes.

Unfortunately, incorporating calculations of theoretical minimum energy use into plant-level energy assessments is costly, complex, and seldom done. As a result, most energy assessment reports do not quantify the maximum energy efficiency potential at the facility.

This paper presents a methodology, called Lean Energy Analysis (LEA), which provides a practical way of thinking about and statistically analyzing plant energy use as guide to the theoretical minimum energy use. The process of identifying energy saving opportunities by considering that "any energy use that does not add value to the product or plant environment is waste" is demonstrated with case study examples. The LEA statistical methodology uses as few as 48 data points, which are readily obtainable through on-site data collection and interviews with facility management. Multivariable change-point models of electricity and natural gas usage as functions of outdoor air temperature and the quantity of production are developed. The statistical models are used to subdivide plant energy use into facility, space-conditioning, and production-related components. The results of this analysis provide a quick and economical method of bracketing energy efficiency potential in a facility and measuring control and direct energy conversion efficiencies.

Energy Trends

During the past few decades, and more dramatically during the past few years, the supply of energy in the US, which is primarily derived from fossil fuels, has exhibited instabilities. While many of these instabilities are attributable to market fluctuations and short-term disruptions in supply, fundamental resource constraints now appear to be imminent. Deffeyes (2001) and Campbell and Laherrere (1998) estimate that global oil production will peak between 2004 and 2009. Even the most optimistic analyses project that world oil production will peak in less than 30 years (Wood et al., 2004). Similarly, estimates of peak global natural gas production range from 2015 (Kissock and Seryak, 2005) to 2030 (Laherrere, 2004).

Despite these possible resource constraints, the U.S. Energy Information Agency (EIA) projects continued growth in industrial energy use. Most of the growth through 2025 is projected to be supplied from increased coal use, while oil consumption is projected to decrease by 18%

(DOE-EIA, 2005). However, increased oil use in the transportation sector is expected to drive total US oil consumption from 20 to 28 million barrels per day. If oil production actually declines, increased renewable energy alone will not supply enough energy to meet demand, based on current growth rates. Remaining options include increased nuclear-based electricity and/or increased energy efficiency.

While nuclear power is an option, safety, waste storage problems and the threat of terrorism have discouraged construction of new nuclear plants. Given the specter of decreasing fossil fuel supplies, uncertainty in nuclear power growth, and small penetration of renewable energy, avoiding economic downturn will require a dramatic increase in energy efficiency.

The Department of Energy's (DOE) Industrial Technologies Program (ITP) has recognized the potential of industrial energy efficiency. DOE-OIT has, through its Industries of the Future program, identified eight of the most energy intensive industries and targeted each with major reductions in energy intensity by 2020. The DOE-OIT proposes to meet these goals through a combination of best-practice applications and new technology.

Theoretical Minimum Energy Use

To bracket energy efficiency potential, the DOE has sponsored several studies on theoretical minimum energy use (Fruehan et al., 2000; Worrell, et al., 2000; Choate and Green, 2003; Energetics, 2004). These studies conclude that theoretical minimum energy use is far less than actual energy use. For example, Ayers (1989) estimated that only 2.5% of US primary energy consumption is used to provide energy services. Table 1 shows the theoretical minimum and actual energy use for the aluminum, steel and ammonia industries as described by Choate and Green (2003), Fruehan, et al. (2000), and Worrell, et al. (2000), respectively.

Table 1: Actual and Theoretical Minimum Energy Consumption

Industrial Process Aluminum	Theoretical Minimum Energy Requirement (kWh (10^9)/year)	Total US Gross Energy Required (kWh (10^9)/year)	Theoretical Minimum Energy % of Actual	Authors
Alumina Refining	0.56	16.24	3.4%	
Anodes Production	9.77	21.86	44.7%	
Aluminum Smelting	22.41	116.36	19.3%	
Primary Casting	1.23	4.56	27.0%	
Secondary Casting	1.15	9.64	11.9%	
Rolling	1.76	6.66	26.4%	
Extrusion	0.75	2.59	29.0%	
Shape Casting	0.84	6.63	12.7%	
Total Aluminum Shape Casting	38.47	184.54	20.8%	Choate & Green
Steel	**GJ/ton product**	**GJ/ton product**		
Liquid Hot Metal	9.8	13.5	72.6%	
Liquid Steel (BOF)	7.9	11	71.8%	
Liquid Steel (EAF)	1.3	2.25	57.8%	
Hot Rolling Flat	0.03	2.2	1.4%	
Cold Rolling Flat	0.03	1.2	2.5%	Fruehan, et al.
Ammonia				
Ammonia Steam Reforming	21.6	35.5	60.8%	Worrell, et al.

Many studies of theoretical minimum energy use rely on the concept of exergy. Exergy is the quantity of work that energy can generate. Theoretical minimum energy use is frequently calculated as the minimum exergy required to produce a given output; thus exergy analysis is a type of minimum energy study. Szargut and Morris (1987) examined exergy use in chemical processes, Wall (1988) investigated exergy use in industry, and Bader and Kissock (2000) examined the exergy use of air compression.

The United Nations Development Programme (UNDP) defines several useful forms of minimum energy use. First, the *theoretical minimum specific energy use* is "for processes that reach the final state of equilibrium at an infinitely slow rate." Industry is not economically viable functioning at an infinitely slow rate, leading UNDP to define *technically achievable minimum energy consumption*, where "technically" indicates that time constraints of the process are taken into account. Finally, the cost of technology is accounted for in *economically achievable minimum energy consumption* (UNDP, 1997). The difference between the theoretical minimum energy use and the actual energy use in an industrial process has been termed the "energy bandwidth" (Energetics, 2004).

While theoretical minimum energy use has been studied as a goal for large-scale energy-reduction efforts, it has not been widely adopted to guide specific energy-reduction efforts. Instead, targeted industrial energy assessments have been shown to provide more practical advice for individual facilities seeking to reduce energy use. Thus far, incorporating calculations of theoretical minimum energy use into energy audits has generally been too costly and complex.

This paper discusses Lean Energy Analysis as an enhancement to traditional methods of conducting energy assessments. LEA provides a practical way to view industrial energy consumption in terms of the energy consumed for operational control and the energy consumed directly for production. Minimizing and eliminating energy not directly consumed for production is an important first step towards achieving minimum theoretical energy use.

Lean Energy Analysis

The 1990's was a decade of renewal for U.S. industry. Economic growth and flat energy prices spurred capital investment in labor saving machinery and improved process equipment. Management structures evolved to systematically address quality and environmental issues in accordance with ISO 9001 and ISO 14001 standards (ISO, 2002; Woodside and Aurrichio, 2000). Product quality improved with the widespread adoption of empirically driven decision tools such as Six Sigma (Tennant, 2003). But perhaps the most important change was the growing adoption of a new paradigm, called Lean Manufacturing, for understanding value and waste in manufacturing processes. The principles of Lean Manufacturing grew from Shewhart's and Deming's work on Statistical Process Control (Thompson, J. and Koronacki, J., 2001). The efficacy of these methods was demonstrated by the success of the Toyota Production System, and documented by Womack and Jones (1996) in their classic "Lean Thinking".

Perhaps the fundamental principal of Lean Manufacturing is that any activity that does not add value to the product is waste. Lean Energy Analysis (LEA) is the specific and rigorous application of this principle to manufacturing energy use. LEA seeks to identify and reduce energy use that is not directly related to production. Like Lean Manufacturing, it is both a way of thinking about the manufacturing process and a set of methods for applying the approach to achieve measurable results.

To think about manufacturing energy use from the LEA perspective, one begins by asking how much energy is directly transmitted to the product and comparing it to the total energy consumed by an operation. The power of this approach for identifying savings opportunities is demonstrated by case study examples in the next section, Energy Use from the Lean Perspective. In addition to a paradigm for thinking about manufacturing energy use, LEA also employs specific statistical and graphical methods to aid in reducing and eliminating non value added energy use. The use of these methods is demonstrated in the section, Statistical Methods for Lean Energy Analysis. In both cases, the use of LEA as a practical method for moving towards theoretical minimum energy use is described.

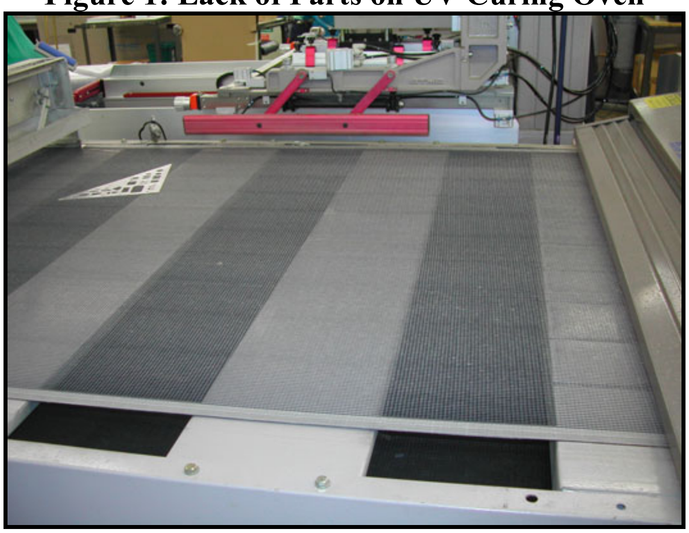
Energy Use from the Lean Perspective

"Lean" energy directly adds value to the product or the production environment. All other uses of energy are waste. Wasted energy includes friction, infiltration, exhaust, oversized and part-loaded equipment and idling equipment. This conceptual framework helps to identify sources of energy waste, so that the waste can be reduced or eliminated. To apply this approach, two questions should be asked when investigating energy saving opportunities for a process: "How much energy value is added to the product/environment?" and "What are the other uses of energy that do not add value?". The following examples illustrate application of this approach.

Conveyor Ovens

Conveyor ovens are commonplace in industry and serve many functions. Examples of conveyor ovens include heat-treating ovens, sintering furnaces, ultra-violet (UV) cure ovens, infra-red (IR) cure ovens and gas-fired drying booths. In this case study, two UV lamps cure ink on plastic templates as they move through the ovens. Figures 1 shows widely spaced parts moving past UV lamps on a mesh conveyor. The parts receive 250-W of UV light for 4.4 seconds over 2.5 feet.

Figure 1: Lack of Parts on UV Curing Oven



A traditional energy assessment may consider installing more efficient UV lamps or a premium efficiency conveyor motor (3% efficiency gain). In the LEA approach, the first question is: "How much energy value is added to the product?" In this case, only the energy needed to cure the ink is value-added. The second question is: "What are the other uses of energy that do not add value?" Here, most of the UV light hits the conveyor rather than a part, thus very little of the energy used to produce the UV light actually cures ink. In addition, even light at wavelengths outside of the UV band is waste, since this light does not cure the ink.

Thinking in these terms makes it apparent that the curing process is vastly inefficient, and opportunities for increasing energy efficiency exist beyond traditional equipment replacement.

In this case, 9-inch x 13.5-inch triangular parts were spaced about every 20 feet on a 5.5-foot wide conveyer. The ink covered about 25% of the part surface. Assuming 75% of the energy consumed by the UV bulbs is used to produce useful UV light, the energy consumed by the UV lamps can be divided into end uses.

Table 2: UV Curing Oven Energy End Use

End Use	% Total
Light hitting conveyor belt	99.23%
Light hitting non-inked part	0.58%
Non-UV light hitting inked part	0.05%
UV light hitting inked part	0.14%
Total	**100%**

As shown in Table 2, only 0.14% of the energy consumed by the UV bulbs adds value to the product. The remaining 99.86% of the energy is waste, and is a target for elimination. Of this, 99.23% of the energy is wasted on the conveyor belt. Thus, LEA shows us is that 99% of the savings potential lies in the low cost and simple act of placing more parts on the belt.

One possible solution to eliminate this source of energy waste would be to turn on the UV lamps only when a part is passing underneath. Unfortunately, using a sensor to turn the lamps on and off is not feasible, because it takes too much time for the bulbs to warm up. Alternatively, the parts could be placed closer together. One way of doing this, without otherwise altering the current production speed would be to turn off one UV bulb, while slowing the conveyor belt speed by half. Thus, the part would still receive 250-W of UV light for 4.4 seconds, but only over 1.25 feet. In this case, the rate of production is not altered, but energy use has been reduced by 50%. Moreover, LEA shows that even more efficiency gains are possible if the parts were placed closer together.

Many conveyor furnace operations show similar opportunities. As noted, exhaust and infiltration are major sources of energy waste, as they add no value to the product. We commonly observe heat-treating furnaces with no production, exhausting all heat to the atmosphere. We also observe dramatically under-loaded IR and gas-fired curing ovens, much like the UV curing oven shown above.

These observations have led us to view energy losses in terms of energy lost during process control, energy lost when converting primary energy from form-to-form, and energy directly applied to the end-use. In many cases, such as this, control losses are much larger than primary energy conversion losses or the energy applied to the end use. When performing energy assessments, we generally don't begin by attempting to independently calculate theoretical minimum energy use for each process based on engineering calculations; however, we've found that thinking in terms of LEA helps us identify large opportunities that we may have otherwise missed and leads us closer to achieving theoretical minimum energy use.

Electroplating Tanks

Large electroplating operations typically have multiple, heated dip tanks, which are heated by gas-fired boilers. Plant air quality is maintained by blowing outdoor air across the open tank tops to capture chemicals, and then exhausting the air outside. The heat generated from natural gas combustion leaves the plant through six ways: the boiler exhaust, the steam piping, the product, the tank waste liquids, the tank sides and the open tank tops. Of these, the greatest source of heat loss is frequently from the open tank tops, due to the large amount of forced convection across the tanks. The smallest energy end use is probably in the value added to the product.

Heat loss from the tank tops can be greatly reduced by installing insulating polypropylene floats. In addition to reducing heat loss, these floats also reduce emissions from the tanks. The reduction in emissions would enable a reduction in airflow across the tanks, and thus create an opportunity for reducing fan energy. In this plant, the air supply and exhaust across the tank tops was imbalanced, creating negative air pressure in the plant. Thus, reducing airflow across the tanks also reduced the negative pressure in the plant, and reducing space-heating requirements.

Thinking in terms of LEA enabled us to clearly see that most of the energy was once again lost trying to control the process. In this case, the control loss was very near the end use. By focusing on the energy end use first, the eventual savings were multiplicative since reducing tank evaporation led to reduced ventilation requirements, which led to reduced fan energy use and reduced space heating energy use. The concept of sequentially focusing on the end use, the distribution system, then the primary conversion system is called the Whole-System Inside-Out approach (Kissock et al., 2001), which is complimentary to LEA thinking.

Statistical Methods for Lean Energy Analysis

As the previous case studies demonstrate, thinking in terms of LEA is a practical and useful technique for "seeing" energy savings opportunities that may otherwise escape notice. In addition, it provides a practical framework for viewing energy use in terms of the theoretical minimum energy use needed by a process. In some cases, such as the UV lamp case study, theoretical minimum energy use can be quantified by engineering calculations. However, time and other constraints frequently inhibit the data collection and analysis required to do so. Moreover, quantifying theoretical minimum energy use for an entire industrial facility is even more complex and time-consuming. Fortunately, LEA's statistical methods can begin the task of disaggregating plant energy use in components that quantify and support the effort of moving toward minimum energy use

The source data for a plant-wide LEA analysis are monthly electricity use, natural gas use, production and outdoor air temperature data. Electricity and natural gas use are generally available from utility billing data. Average daily temperatures from 1995 to present for over 300 cities around the world are available from the UD/EPA Average Daily Temperature Archive (http://www.engr.udayton.edu/weather/). Manufacturing plants typically track production. The data should be averaged, to eliminate the variance in days per billing period. Using these methods, only 48 monthly data points (12 months of electricity, gas, temperature and production data) are required to perform a basic Lean Energy Analysis.

Using these data, plant energy use is modeled as a function of outdoor air temperature and the quantity of production using multi-variable change-point models. These models were originally developed to model energy use as a function of outdoor air temperature and other influential variables in buildings. (Kissock et al., 1998a; Kissock et al., 2003). However, they are also applicable for analyzing industrial energy use.

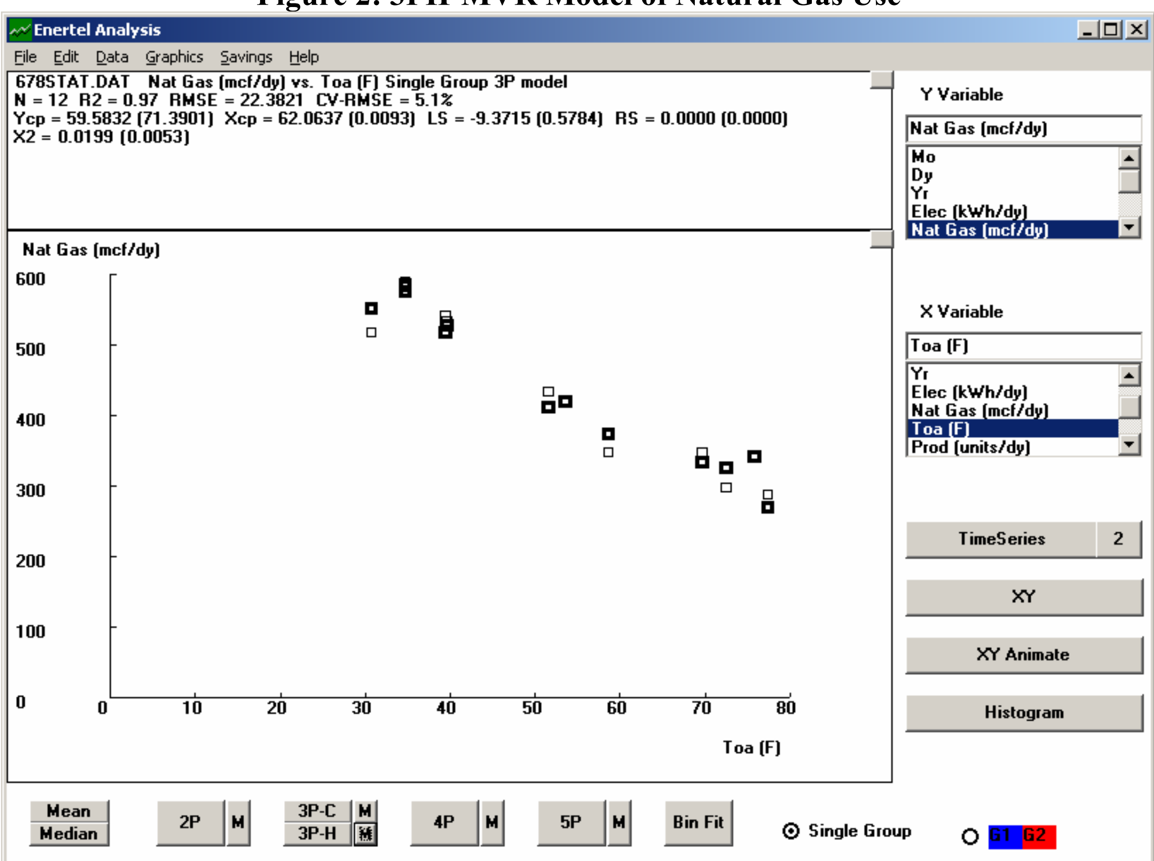
The statistical models used in LEA could be created using standard statistical software applications. However, specialized software for LEA modeling, such as Energy Explorer (Kissock, 2000), significantly reduces the required data handling and statistical modeling, and provides graphical output that increases intuitive understanding of the results. In addition, the multivariable change-point models described above are included in Energy Explorer. The case studies below demonstrate how Energy Explorer to quickly develops LEA models of gas and electricity use.

Case Study Example of Developing an LEA Model of Natural Gas Use

Time trends of natural gas use verses outdoor air temperature or production show that gas use is inversely correlated with temperature and somewhat correlated with production. However, taken separately, the affects of the temperature and production on gas use are confounded. LEA statistical analysis disaggregates the affects of temperature and production.

Figure 2 shows the regression results of a three-parameter heating model of natural gas use as a function of outdoor air temperature that also includes production as an additional independent variable. This model is called a 3PH-MVR model since it includes the capabilities of both a three-parameter heating model of energy use versus temperature (3PH), plus a multivariable-regression model (MVR). The model's R^2 of 0.97 indicates that virtually all of the variation in natural gas use is correlated to the variation in outdoor air temperature and production. The model's coefficient of variation of the root mean square error (CV-RMSE) of 5.1% indicates that it can predict future natural gas use within $\pm$10.2% at the 95% confidence level (Kissock et al., 1998a).

Figure 2: 3PH-MVR Model of Natural Gas Use



3PH-MVR model of natural gas use as function of both outdoor air temperature and production. Measured natural gas use (light squares) and predicted natural gas use (bold squares) are plotted against outdoor air temperature.

Equation 1 shows a general form of a 3PH-MVR equation for predicting natural gas use, NG, as a function of outdoor air temperature Toa and quantity of units produced, P. Equation 2 shows the equation using the regression coefficients from Figure 7.

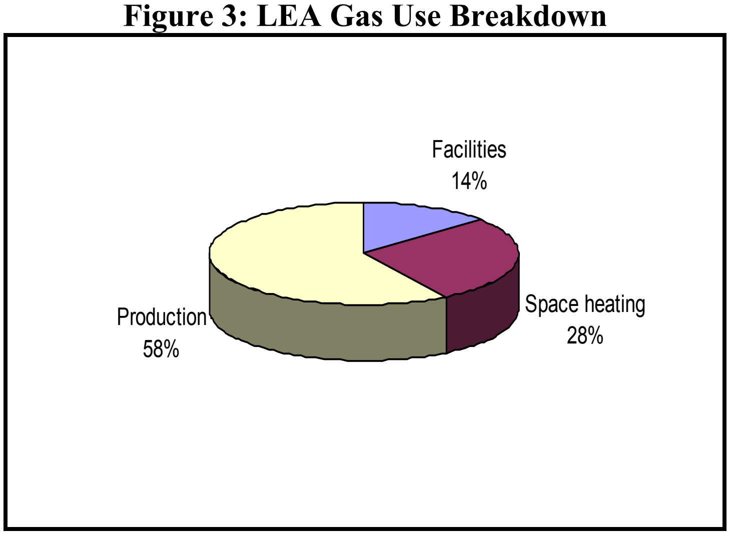
$$NG = Ycp + LS \times (Xcp - Toa)^{+} + (X2 \times P) \; NG \text{ (mcf/day)} \quad (1)$$
$$NG = 60 \text{ (mcf/dy)} + 9.4 \text{ (mcf/dy-F)} \times [62 \text{ (F)} - Toa \text{ (F)}]^{+} + 0.02 \text{ (mcf/unit)} \times P \text{ (units/dy)} \quad (2)$$

The first term of this equation, Ycp, represents energy use that does not vary with either weather or production; we call this *facility* energy use. From a lean energy perspective, *facility* energy use does not add value to the product or environment and is waste. Thus, eliminating *facility* energy use is the first goal for achieving minimum theoretical energy use. The second term, LS, represents weather-dependent energy use. In this case, natural gas use for space heating increases whenever the outdoor air temperature is less than the building balance point, Xcp, as indicated by the superscript "+". The third term, X2, represents production-dependent energy use. The fact that space heating gas use only increases at temperatures below 62° F, and that the true relationship between gas use and production could only be identified in a multi-variable model, demonstrates the power and necessity of using multivariable change-point models to accurately describe plant energy use.

$$E_{facility} = 60 \text{ (mcf/day)}$$
$$E_{weather\text{-}dependent} = 9.4 \text{ (mcf/day-F)} \times [62 \text{ (F)} - Toa \text{ (F)}]^{+}$$
$$E_{production\text{-}dependent} = 0.02 \text{ (mcf/unit)} \times P \text{ (units/day)}$$

These equations can be used to break down total natural gas use into calculated production-dependent, weather-dependent and facility components (Figure 3). In this case, only about 14% of natural gas use is unrelated to production or weather. From a lean energy perspective, the relatively small fraction of *facility* energy use indicates good process control.

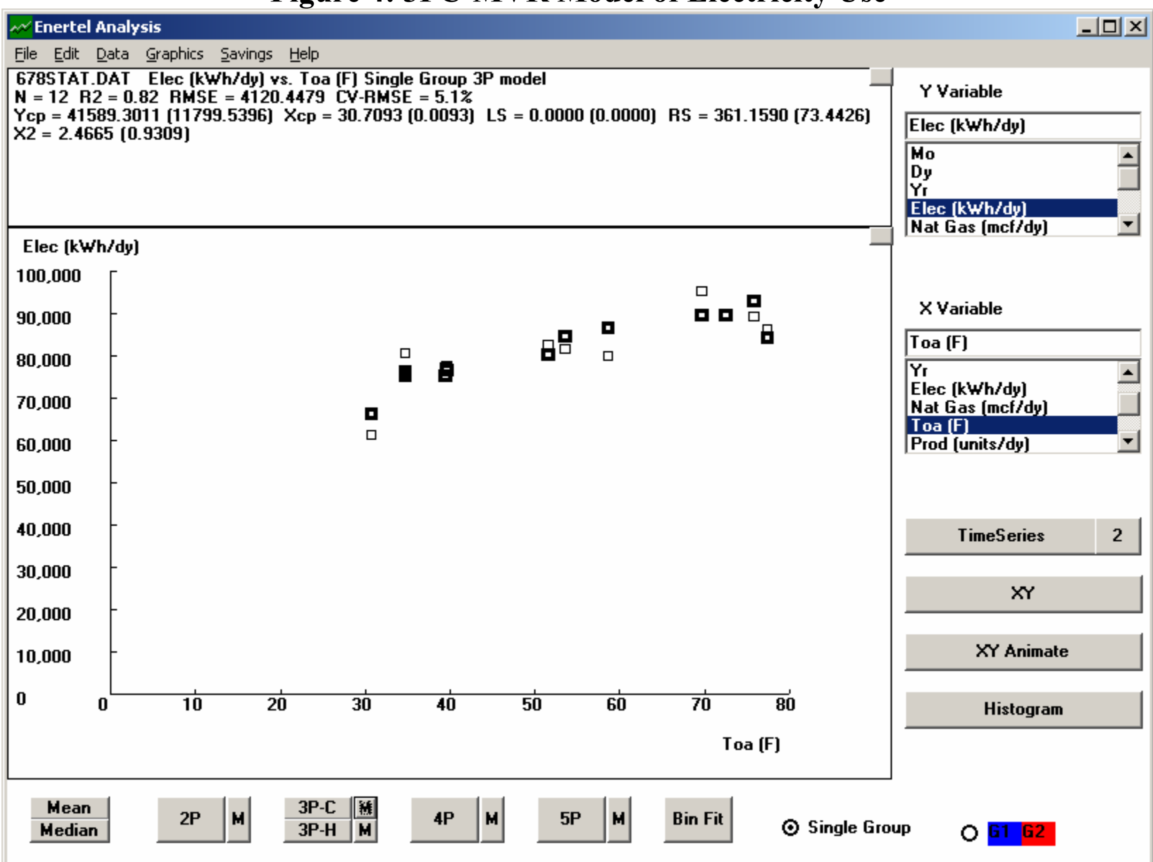
Figure 3: LEA Gas Use Breakdown



Case Study Example of Developing an LEA Model of Electricity Use

The procedure demonstrated above for modeling natural gas use can also be applied to electricity use. For example, Figure 9 shows a three-parameter cooling model of electricity use as a function of outdoor air temperature, that also includes production as an independent variable. The model's R^2 of 0.82 indicates that most of the variation in natural gas use is correlated to the variation in outdoor air temperature and production. The model's CV-RMSE of 5.1% indicates that model can predict future natural gas use with an accuracy of about $\pm$10.2% at the 95% confidence level (Kissock et al. 1998a). Using the model shown in Figure 4, production, air conditioning and facility energy use are 39%, 10% and 51% of total plant energy use, respectively.

Figure 4: 3PC-MVR Model of Electricity Use



Results of three-parameter cooling model of electricity use as function of both outdoor air temperature and production. Measured electricity use (light squares) and predicted electricity use (bold squares) are plotted against outdoor air temperature.

In this case, about 51% of electricity use is unrelated to production or weather. This suggests substantial potential for reducing unnecessary and non-value added "facility" electricity use. Typical sources of facility energy use include lights left on over areas where production has stopped, air compressors that continue to draw near full load power even when producing little compressed air, production machinery that is not turned off when not in use and pumps and fans that run continually, independent of the outdoor air temperature or production.

Although it is possible that some of these functions may be required for production or to maintain the plant environment, our experience has invariably shown that facilities with large fractions of *facility* energy use have substantial energy savings potential in these areas.

LEA Modeling and Theoretical Minimum Energy Use

The previous examples demonstrated how LEA statistical modeling can quickly disaggregate energy use into *facility*, production-dependent, temperature-dependent components. In terms of lean manufacturing, *facility* energy use does not add value to the work environment or product, and is waste. Energy waste can be categorized into primary energy conversion inefficiency and process control inefficiency. For example, energy consumed by an air compressor when running unloaded is a control loss, while energy consumed compressing air is for direct energy conversion. In commercial buildings, reheat or mixing hot and cold air streams are control losses, while energy delivered to meet the zone loads is for direct energy conversion.

It follows that equipment, processes and whole facilities have both control and primary energy conversion efficiencies. For manufacturing facilities, the control efficiency is the compliment of the *facility* energy use. For example, in the previous case studies, the control efficiency of electrical energy use was 49% and the control efficiency of gas use was 86%. Reducing "facility" energy use can be thought of as improving the control of the plant production and space conditioning.

Beyond minimizing facility energy use, the primary energy conversion efficiencies of production and space conditioning can also be improved. LEA statistical methods would measure this improvement in the values of the production-dependent and weather-dependent regression coefficients. For example, in the previous case study increased insulation may reduce the value of the model coefficient for production-dependent gas use below the current 0.0199 mcf/unit. Similarly, higher-efficiency motors may reduce the value of the model coefficient for production-dependent electricity use below the current 2.47 kWh/unit.

LEA cannot determine the minimum value for these coefficients, which would represent the theoretical minimum energy use. As stated above, the determination of this number is dependent upon a number of assumptions, which may vary from case-to-case. However, if exergy or other engineering methods were used to quantify the minimum energy use, these values could be compared to the values of the regression coefficients. For example, if the minimum gas use necessary to melt one unite of aluminum were determined be 0.005 mcf/unit, then the direct energy conversion efficiency of production gas use would be about 0.005 / 0.0199 = 25%.

This suggests that LEA statistical methods can divide plant energy use into three basic end-uses: production energy use, plant environment energy use, and facility energy use (process control inefficiency).

The production component of energy use includes theoretical minimum process energy and energy conversion inefficiency. The space-conditioning component of energy use includes theoretical minimum plant environment energy use and energy conversion inefficiency. Thus, energy conversion inefficiencies are confounded within the coefficients for theoretical minimum energy use. However, control inefficiencies are not confounded, but quantified, by the "facility" component of plant energy use.

Conclusions

In the near future, the world economy will be faced with an energy crisis with no ready solution. Decreasing oil and natural gas production will collide with increased demand from a growing global economy. If free markets prevail, these pressures will increase the cost of energy, which will in turn slow economic growth and spur efforts to conserve energy and develop other sources of energy. Increased use of coal and nuclear power are associated with serious environmental, safety and security problems, and economic slowdown is not the preferred outcome. Renewable energy continues to grow at an impressive rate; however, its relatively small fraction of current energy use makes it unlikely that it can reconcile the prospective gap between supply and demand in the short term.

This suggests that a dramatic increase in energy efficiency may be the most viable solution. Previous efforts to determine the theoretical minimum energy use of major industrial processes indicate that industrial processes are currently so energy-inefficient that energy efficiency may indeed be able to generate the required reductions in energy use. These efforts bracketed energy efficiency potential by defining the "energy bandwidth", the difference between theoretical minimum and actual energy use. While this bracket has been applied on the macro-program scale, it has yet to be widely used at the level of reducing individual facility level energy use.

In this paper, we proposed that a new approach, called Lean Energy Analysis, can guide the reduction of energy use in individual facilities toward theoretical minimum energy use. The roots of LEA are in Lean Manufacturing, which defines waste as any effort that does not add value to the product. Similarly, LEA seeks to identify, quantify and eliminate non-value added energy use. Case studies showed how simply learning to see energy from a lean perspective is helpful in identifying large energy saving opportunities that might otherwise go unnoticed. In addition, LEA statistical methods were shown to quickly quantify facility, production and weather-dependent components of energy use. The *facility* component is largely a function of *control* inefficiency and represents the first target for reducing plant energy use to theoretical minimum. Thus, LEA appears to be a practical method for identifying and implementing the dramatic improvements in energy efficiency required to meet the coming energy challenges.

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