Understanding Industrial Energy Use through Sliding Regression Analysis

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ABSTRACT

Due to rising energy costs and global climate change, many industries seek to improve their energy efficiency. This paper describes a three-step method to analyze utility billing, weather, and production data to understand a company's energy performance over time. The method uses regression modeling of utility billing data against weather and production data. The regression models are then driven with typical weather and production data to calculate the 'normal annual consumption', NAC. These steps are repeated on sequential sets of 12 months of data to generate a series of 'sliding' NACs and regression coefficients. The method can quantify successful energy efficiency initiatives and lend insight into the cause of the energy savings. In addition, the method is able to proactively identify energy saving opportunities. The method is demonstrated with a case study. The case study shows that the method is able to disaggregate energy use into weather, production and independent components, accurately measure changes in plant energy efficiency, lend insight into the nature of the those changes, identify savings opportunities and identify changes in overall process control.

Introduction

Non-renewable fossil fuels account for 82% of the world's energy consumption (Boyle 2004). The use of fossil fuels is the primary contributor to global climate change and the source of the majority of all air pollution (US EPA 1994; IPCC 2007). The emergence of a global marketplace has increased the demand for non-renewable fossil fuels and energy costs have increased (Deffeyes 2001). With potential future legislation restricting carbon emissions from fossil fuels, energy costs are further projected to increase. This has the potential to put some companies at risk for long-term financial gain. To maintain future economic viability, insulate against potential fuel shortages and mitigate potential risks of global climate change, industries must proactively improve their energy efficiency.

This paper describes a three-step method to analyze utility billing, weather, and production data to understand a company's energy performance over time. The method uses regression modeling of utility billing data against weather and production data. The regression models are then driven with typical weather and production data to calculate the 'normal annual consumption', NAC. These steps are repeated on sequential sets of 12 months of data to generate a series of 'sliding' NACs and regression coefficients. The method can quantify successful energy efficiency initiatives and lend insight into the cause of the energy savings. In addition, the method is able to proactively identify energy saving opportunities. Thus, the method is able to derive a significant quantity of actionable information from simple utility bills and readily available weather and production data.

Previous similar efforts include the PRInceton Scorekeeping Method, PRISM, which regressed energy use versus variable-base degree-days (Fels, 1986a). The method described here uses temperature change-point models instead of degree-day models and includes production as an independent variable. Temperature change-point models were described by Kissock et al. (1998) and Kissock et al., (2003). The temperature change-point model method was extended to include additional independent variables by Kissock et al. (2003) and Haberl et al. (2003). This paper applies this method to industrial energy use, and extends the method by calculating NAC and then by calculating sliding NAC. Previous efforts to interpret regression coefficients in industrial energy use models include Kissock and Seryak (2004a; 2004b) and Patil et al. (2005). These multi-variable change-point models are used by US-EPA Energy Star Buildings program (Kissock 1997) to weather normalize building energy use and in the ASHRAE Inverse Modeling Toolkit (Kissock et al. 2001) in support of measurement and verification efforts. This paper describes the method and applies the method to a case study.

Overview of the Method

The method of using 'sliding' NAC analysis to identify facility and production performance over time is accomplished through three sequential steps. These steps are developing energy signature models, calculating normal annual consumption, and performing 'sliding' NAC analysis. Each step is discussed individually below.

Description of Data and Software Tools

Utility bills are widely available and accurately describe the amount of fuel or electricity delivered to facilities. Thus, this method uses utility bills as the principle source of energy use data.

The method uses both actual and typical weather data. Actual average daily temperatures for 157 U.S. and 167 international cities from January 1, 1995 to present are available free-of-charge from the University of Dayton Average Daily Temperature Archive (Kissock 1999a). Typical weather data is derived from TMY2 data files (NREL 1995). TMY2 files contain typical meteorological year (TMY) data sets derived from the 1961-1990 National Solar Radiation Data Base (NSRDB). These files include typical hourly values of solar radiation, ambient temperature, ambient humidity and wind speed for a 1-year period.

This method also uses both actual and typical production data. Actual production data is generally available from facility management or accounting departments. Typical production data can be derived from historical averages, budgeted values, or projected production. The case studies illustrating the method use historical averages for typical production.

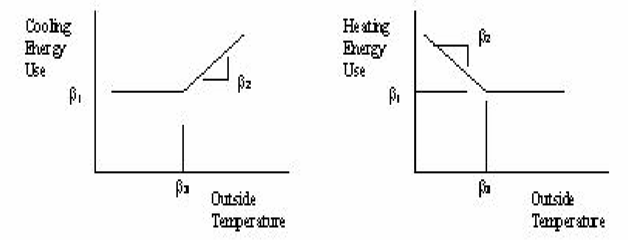
The algorithms used to generate multi-variable change point models are described in the previous references. These methods have been incorporated into two software applications that were used for this analysis: Energy Explorer (Kissock 2005) and ETrackerC (Kissock, 2006).

Step 1: Developing Energy Signature Models

The first step of the method is to create statistical models of each facility's electricity and fuel use as functions of weather and production using utility billing data, actual weather data, and actual production data.

In many industrial facilities, the weather dependence of energy use can be accurately described using a three-parameter change-point model. Three-parameter change-point models describe the common situation when cooling (heating) begins when the air temperature is more (less) than some building balance temperature. For example, consider the common situation where electricity is used for both air conditioning and production-related tasks such as lighting and air compression. During cold weather, no air conditioning is necessary, but electricity is still used for production purposes. As the air temperature increases above some balance-point temperature, air conditioning electricity use increases as the outside air temperature increases (Figure 1a). The regression coefficient β_1 describes non-weather dependent electricity use, and the regression coefficient β_2 describes the rate of increase of electricity use with increasing temperature, and the regression coefficient β_3 describes the change-point temperature where weather-dependent electricity use begins. This type of model is called a three-parameter cooling (3PC) change point model. Similarly, when fuel is used for space conditioning and production-related tasks, fuel use can be modeled by a three-parameter heating (3PH) change point model (Figure 1b).

Figure 1. (a) 3PC (Cooling) and (b) 3PH (Heating) Regression Models



These basic change-point models can be extended to include the dependence of energy use on the quantity of production by adding an additional regression coefficient. The functional forms for best-fit multi-variable three-parameter change-point models for cooling energy use, E_c, (3PC-MVR) and heating energy use, E_h, (3PH-MVR), respectively, are:

$$E_C = \beta_1 + \beta_2 (T - \beta_3)^+ + \beta_4 \cdot P \tag{1}$$

$$E_H = \beta_1 - \beta_2 (\beta_3 - T)^+ + \beta_4 \cdot P \tag{2}$$

where β_1 is the constant term, β_2 is the temperature-dependent slope term, β_3 is the temperature change-point, and β_4 is the production dependent term. T is outdoor air temperature and P is the quantity of production. The superscript + notation indicates the parenthetic term evaluates to zero when the value of the enclosed term is negative.

The use of a single regression coefficient, β_4, and a single metric of production, P, is arbitrary; additional terms can be added to account for multiple products. The number of production variables needed to characterize plant energy use depends on the plant and process. In many plants, such as auto assembly plants or foundries, the relationship between energy use and production is accurately characterized by a singe variable. In other plants with a heterogeneous product mix, multiple variables for the most energy-intensive products may be needed. In this paper, the method is demonstrated using one production variable; however, the methodology is unchanged with addition production variables.

In Equations 1 and 2, the β_1 term represents energy use that is independent of both weather and production, such as lighting energy use in plants with limited daylighting. The $\beta_2 \cdot (T - \beta_3)^+$ or $-\beta_2 \cdot (\beta_3 - T)^+$ term represents outdoor air temperature-dependent energy use. Because several studies have shown that outdoor air temperature is the single most important weather variable for influencing energy use in most buildings, this is referred to as weather-dependent energy use. (Fels 1986b; Kissock et al. 1998) In cases for which the weather dependent term represents space-conditioning energy use, the coefficient, β_2, represents the overall building load coefficient, UA, divided by the efficiency of the space conditioning equipment, η. In the case of 3PC or 3PC-MVR models, this coefficient is referred to as the cooling slope (CS). Similarly, in the case of 3PH or 3PH-MVR models, this coefficient is referred to as the heating slope (HS). The coefficient, β_3, represents the building balance temperature, which is the outdoor air temperature below which heating energy is used or above which cooling energy is used. The $\beta_4 \cdot P$ term represents production-dependent energy use. Using these terms, these simple regression equations can statistically disaggregate whole-plant energy use into independent, weather-dependent and production-dependent components. The interpretation and use of this technique is called Lean Energy Analysis (Kissock and Seryak, 2004a; Kissock and Seryak, 2004b and Patil et al. 2005, Kissock and Eger, 2006; Eger and Kissock, 2007) and is useful for identifying energy saving opportunities, measuring energy effects of productivity changes, developing energy budgets, and measuring energy savings.

Step 2: Normalize Annual Energy Consumption

Utility bills show the actual annual energy consumption during a billing period. However, that energy consumption might be affected by unusual weather or production. This makes it difficult to assess a facilities energy performance over time when weather or production changes. Both of these problems can be eliminated by driving the energy signature model with "typical" weather and production. The resulting annual energy use is called the Normalized Annual Consumption, (NAC). To calculate the NAC, the energy signature models developed in Step 1 are driven with typical weather data from TMY2 files and typical production data from historical records. Thus, NAC represents the "noise-free" energy use of a facility after changes due to abnormal weather and production variances have been removed. As such, NAC reveals the true energy characteristics of facilities and manufacturing processes, and allows comparison of facility energy use over time.

Step 3: Sliding NAC Analysis

The change in energy characteristics of a manufacturing facility can be determined by comparing the facility's NAC during sequential 12-month periods. This is called a 'sliding' NAC analysis. To calculate the 'sliding' NAC, an energy-signature model is created for each set of 12 sequential months, and then driven with typical weather from a TMY2 file and typical production from a typical independent variable (TIV) file to create a sequence of NACs. The sliding NAC analysis illustrates how the building's fundamental energy use characteristics change over time. Figure 2 shows a graphical representation of how a 'sliding' NAC is calculated using the sequential dataset.

Figure 2: Graphical Representation of Sliding NAC

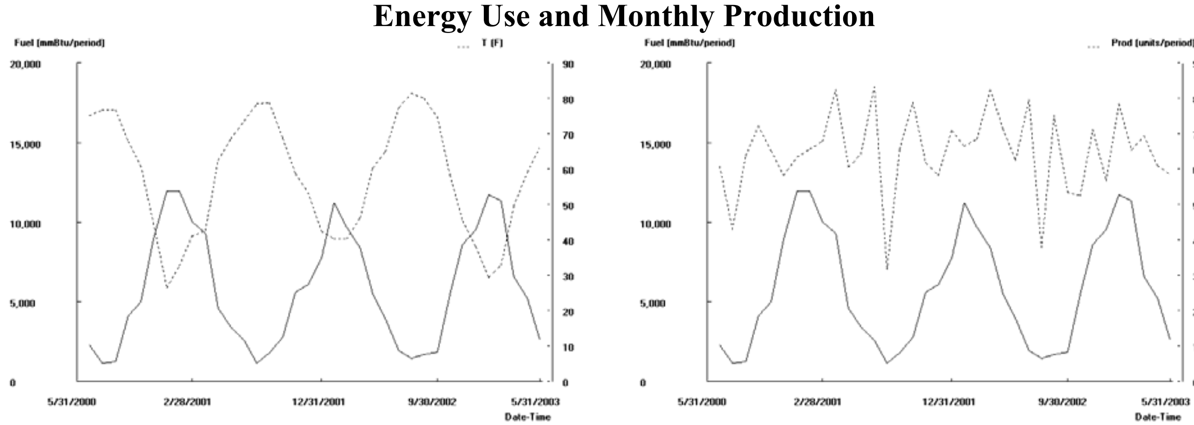
Sliding NAC Analysis Data Set	Data set 1												Data set n											
Months	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Data set (Year)	Year 1												Year n											
Months	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Sliding NAC Analysis Data Set		Data set 2																						

Additional information can be derived by tracking the values of the model coefficients over time. Changes in NAC are caused by changes in model coefficients. Thus, a sliding analysis of model coefficients can identify the cause of a change in NAC. Sliding NAC and coefficient analysis provide a powerful lens through which a facility's fundamental energy performance, including building and production energy use, can be understood. Interpreting results can indicate specific areas of improvement, areas where improvements have already been made, and the persistence of energy-reduction measures over time.

Case Study 1

This case study illustrates the method when both weather and production influence facility energy use. Figure 3a shows a time trend of natural gas energy use and average outdoor air temperature. Similarly, Figure 3b shows a time trend of natural gas use and monthly production. A quick inspection of Figures 3a shows that natural gas use increases in winter months and decreases during summer months. This indicates a strong weather dependence of natural gas energy use. Alternatively, Figure 3b does not show any conclusive indication that natural gas energy use varies with production.

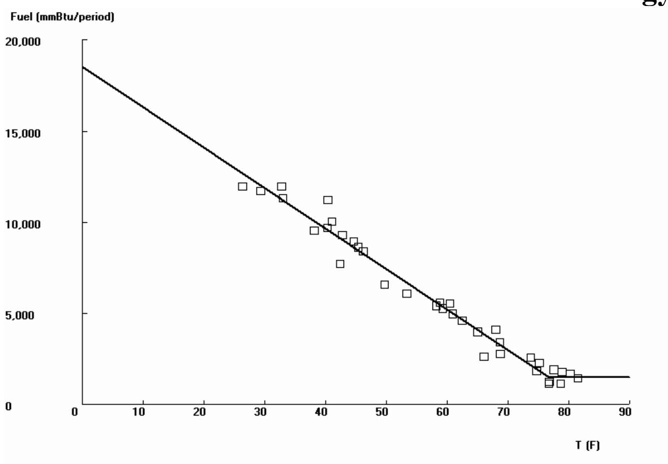
Figure 3: (a) Natural Gas Energy Use and Outdoor Air Temperature and (b) Natural Gas Energy Use and Monthly Production



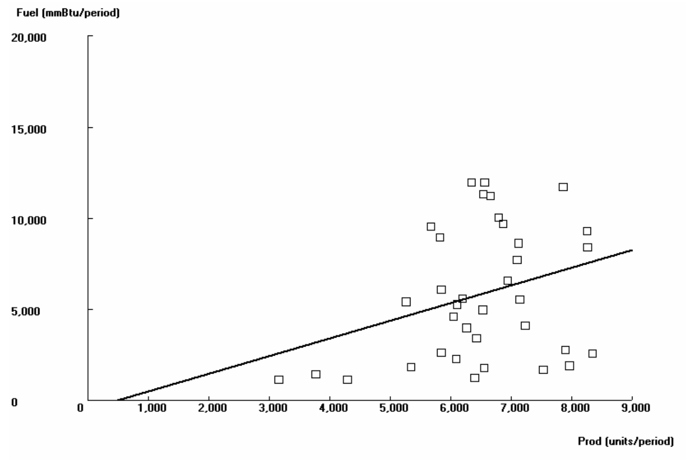
(a) (b)

Figure 4a shows a three-parameter heating (3PH) model of natural gas energy use as function of outdoor air temperature. Table 1 shows the model's coefficients and statistical indicators. The R^2 and CV-RMSE statistics indicate the model is able to adequately predict natural gas energy use with respect to outdoor air temperature. Figure 4b shows a two-parameter (2P) model of natural gas use as a function of production, where production data is scaled to increase the resolution of the model coefficients. The model indicates a very slight increase in natural gas use as production increases. Table 2 shows the model coefficients and statistical indicators. The very low R^2 statistic indicates production alone is a poor predictor of natural gas energy use.

Figure 4: (a) 3PH Model of Natural Gas Energy Use As a Function of Weather and (b) 2P Model of Natural Gas Energy Use As a Function of Production



(a)



(b)

Table 1: 3PH Model Coefficients and Statistical Indicators

Coefficient	Description	Units	Value ± Standard Error
R^2			0.98
CV-RMSE			10.0%
β_1	Independent Fuel-use	mmBtu/period	1485.13 ±151.68
β_2	Temperature Dependence	mmBtu/period-F	-222.28 ±6.045
β_3	Balance-Point Temperature	F	76.65 ±0.011

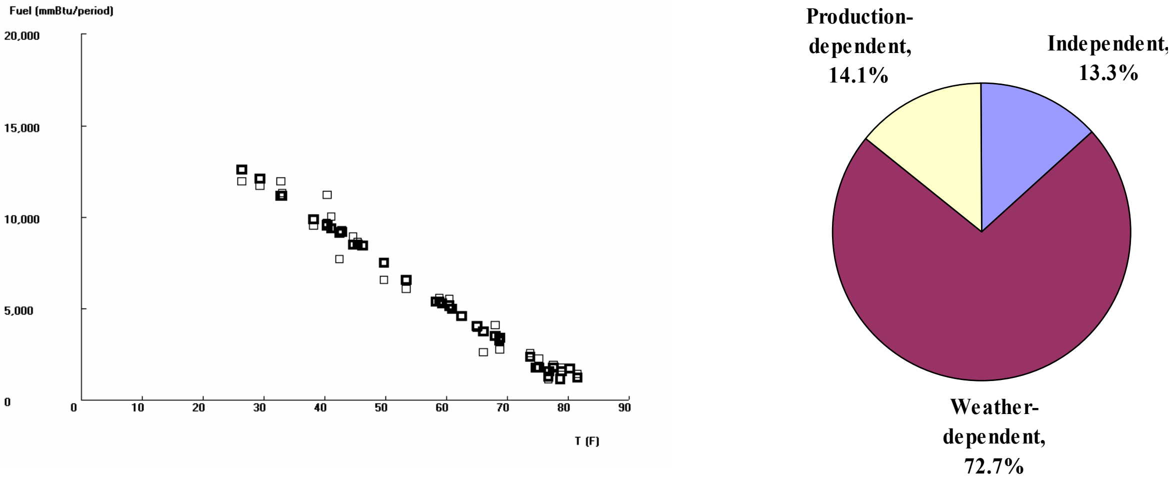
Table 2: 2P Model Coefficients and Statistical Indicators

Coefficient	Description	Units	Value ± Standard Error
R^2			0.10
CV-RMSE			60.6%
β_1	Independent Fuel-use	mmBtu/period	-480.85 ±3,340.75
β_4	Production-Dependent	mmBtu/1000 lbs	0.97 ±0.51

Figure 5 shows the 3PH-MVR model. Light squares indicate the actual natural gas energy use and dark squares indicate the natural gas energy use predicted by the model. Model coefficients and goodness-of-fit statistics are shown in Table 3. An R^2 of 0.98 and CV-RMSE of 9.8% indicates the 3PH-MVR model is able to account for almost all of the variation in fuel use.

From the 3PH-MVR model, natural gas energy use can be disaggregated into constituent components according to the model coefficients. Figure 5b shows this disaggregated breakdown. Independent natural gas use accounts for about 13.3% of the total. Weather-dependent natural gas use accounts for about 72.7% of the total. Production-dependent natural gas use accounts for about 14.1% of the total. These data indicate facility space heating is the largest contributor to natural gas use.

Figure 5: (a) 3PH-MVR Model of Fuel Use As a Function of Weather and Production and (b) Natural Gas Energy Use Breakdown



(a) (b)

Table 3: 3PH-MVR Model Coefficients and Statistical Indicators

Coefficient	Description	Units	Value ± Standard Error
R^2			0.98
CV-RMSE			9.8%
β_1	Independent Fuel	mmBtu/day	768.41 ±543.47
β_2	Temperature Dependent	mmBtu/day-F	-221.15 ±6.24
β_3	Building Balance	F	76.22 ±0.011
β_4	Production Dependent	mmBtu/lb	0.126 ±0.0859

Figure 6 shows the ‘sliding’ NAC (solid line) and actual fuel use (dashed line) over a 36 month period. During the first several months, the NAC and actual consumption were approximately equal. After about six months, the actual consumption declines while NAC stays approximately constant. Thus, considering only annual consumption would suggest that the plant had become more energy efficient. However, the fact that NAC remains constant and most energy use is weather dependent indicates that consumption actually decreased because weather conditions during this time period were mild compared to typical weather patterns. In contrast, NAC does decline over the last six months, which indicates that the plant did become more energy efficient over this period. Over the entire period, the NAC declined by about 7%, which indicates that after the effects of variable weather and production were eliminated, the plant became about 7% more efficient over the period of analysis.

Figure 6: Sliding NAC Analysis and Actual Facility Fuel Use

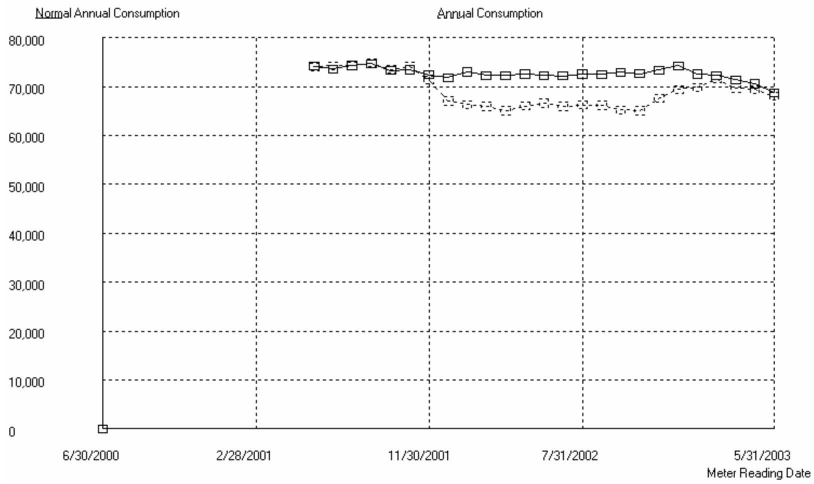
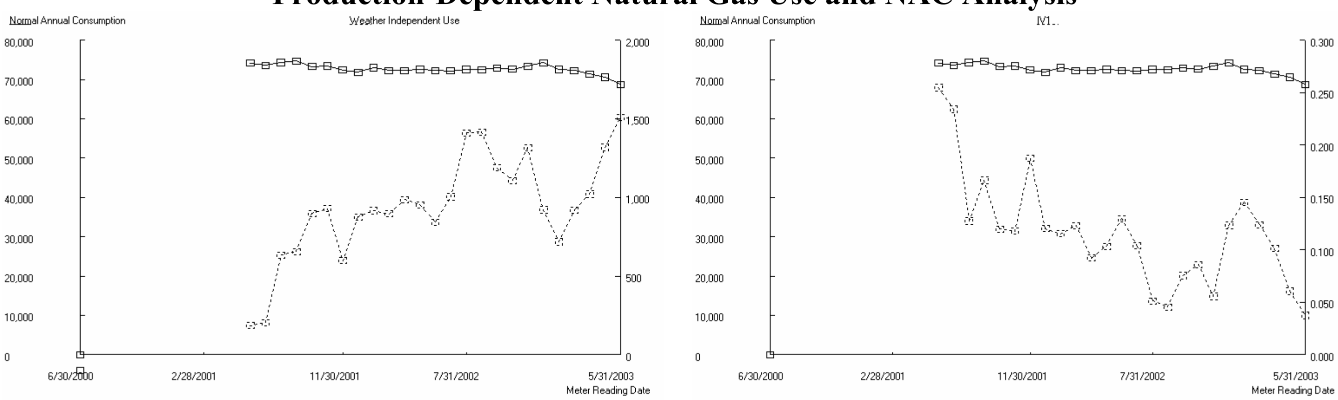


Figure 7a shows how the independent natural gas energy use and NAC vary over time. Similarly, Figure 7b shows how the production fuel use (IV1) and NAC vary over time. For both Figure 7a and 7b, the solid line is the NAC and the dashed line is independent fuel use and production fuel use, respectively.

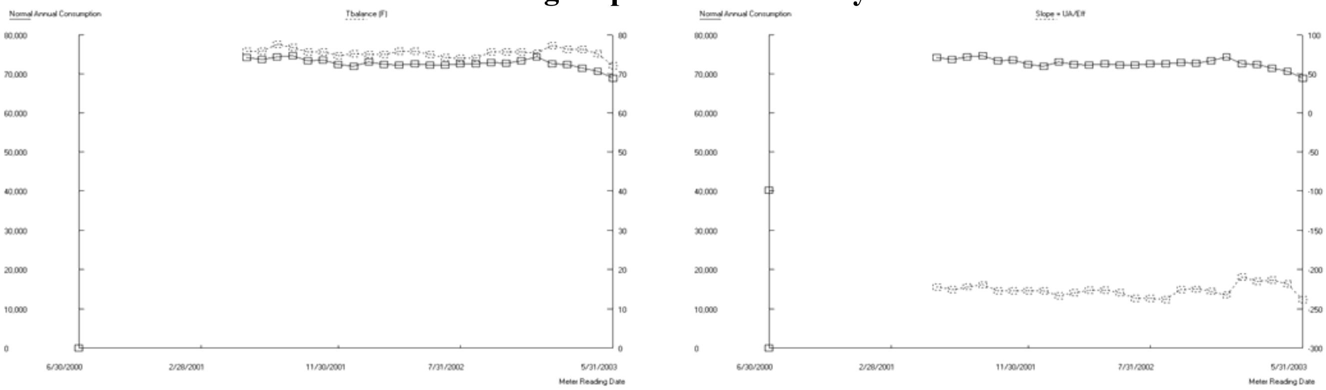
Figure 7: (a) Sliding Independent Natural Gas Use and NAC Analysis and (b) Sliding Production-Dependent Natural Gas Use and NAC Analysis



(a) (b)

Figure 8a shows how the balance-point temperature $T_{balance}$ and NAC over time. Similarly, Figure 8b shows how the heating slope and NAC vary over time. For both Figure 8a and 8b, the solid line is the NAC and the dashed line is the balance-point temperature and heating slope, respectively. Figure 8a indicates the balance-point temperature remained constant at about 75 F until the last 6 months of analysis. At this time, the balance-point temperature decreased, which was probably caused by lower thermostat settings in the plant. In Figure 8b, the heating slope at the beginning and end of this six month period remained constant. The net effect was that the plant became more energy efficient due to lower thermostat settings.

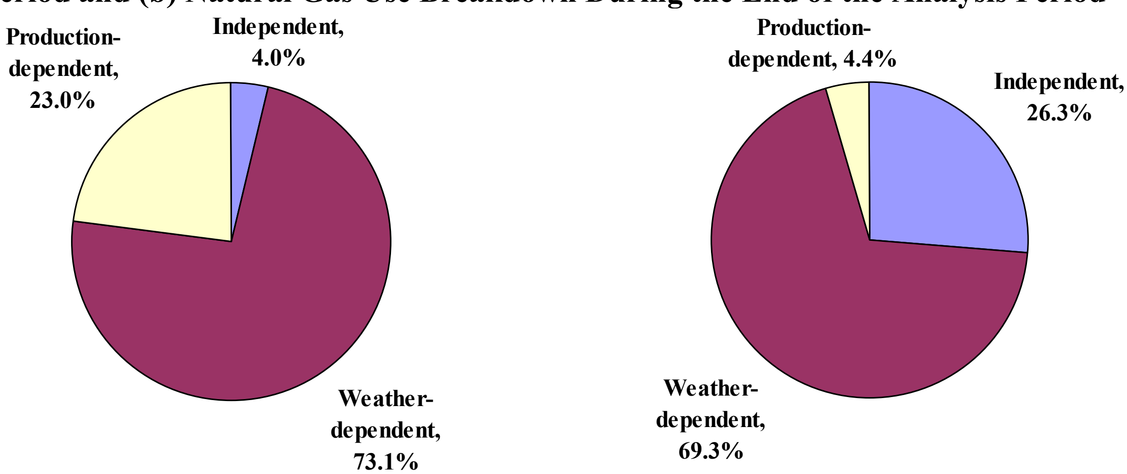
Figure 8: (a) Sliding Balance-Point Temperature and NAC Analysis and (b) Sliding Heating Slope and NAC Analysis



(a) (b)

Figure 9a and 9b show the natural gas use breakdowns during the initial and last 12-month periods of the analysis. These breakdowns show a progressive shift of energy use from production-dependent to independent energy use. This indicates a degradation in process control, since energy use not associated with production is characterized was waste according to principles of Lean Energy Analysis.

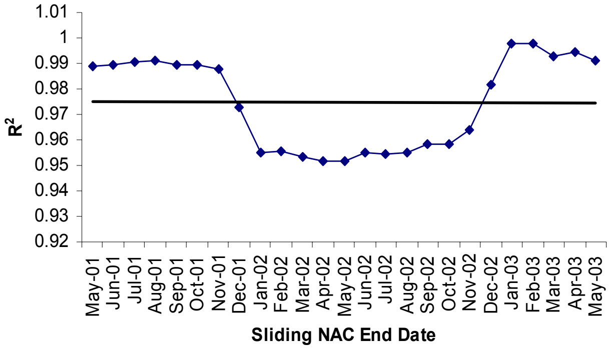
Figure 9: (a) Natural Gas Energy Use Breakdown During the Beginning of the Analysis Period and (b) Natural Gas Use Breakdown During the End of the Analysis Period



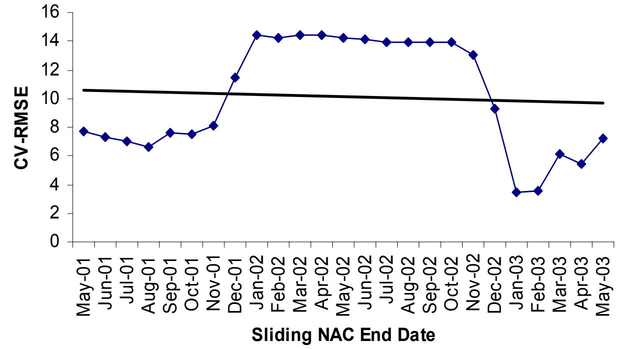
(a) (b)

Another view into process control can be achieved by tracking model R2 and CV-RMSE over time. Declining R^2 and increasing CV-RMSE indicate that energy use is not correlating with weather or production, which generally indicates declining process control. In this case, Figures 10a and 10b show that both statistics remained relatively constant, which indicates little change in overall process control.

Figure 10: (a) Time Trend of R^2 and (b) Time Trend of CV-RMSE



(a)



(b)

Conclusion

This paper describes a three-step method to analyze monthly utility billing, weather and production data to target industrial facility's energy use. The first step of the method is to create multivariable three-parameter change-point models of energy use as a function of weather and production. The second step is to drive the models with normal weather from TMY2 files and normal production data to calculate the Normalized Annual Consumption (NAC). The third step is to calculate sliding NACs and model coefficients with each set of 12 sequential months of utility data. The method was demonstrated with a case study. The case study shows that the method is able to disaggregate plant energy use into weather, production and independent components, accurately measure changes in plant energy efficiency, lend insight into the nature of the those changes, identify savings opportunities and identify changes in overall process control.

Acknowledgement

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