Assessing the Impact of Behavioral Energy Efficiency Measures: A Simulation Approach

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ABSTRACT

In an effort to optimize production with respect to energy, the Northwest Energy Efficiency Alliance (NEEA) sponsored a study to determine potential energy savings in the food processing industry from behavioral modifications by plant personnel. Previously, measurement procedures of plant managers did not account for changes in weather or production flows and their impact on energy consumption. As a result, the initial estimates by management failed to address uncertainty and the facility's dynamic environment.

The main focus of this paper is to analyze the effects of behavioral modifications on energy consumption. To measure these effects, NEEA supplied 3 years of facility production and billing data. This data made it possible to examine the effects of their energy efficiency efforts by first testing for structural changes at the advent of the behavioral modifications, estimating marginal rates of energy consumption and finally, establishing a range of future outcomes using a Monte Carlo simulation.

Manufacturing facilities attempting to optimize their production have become increasingly interested in optimizing energy usage. The result is a focus on industrial energy consumption per unit of output. This paper outlines a methodology for estimating the impact of behavioral changes on facility energy consumption where traditional methodologies fall short. The advantage gained in a Monte Carlo simulation is an improved estimation that incorporates uncertainty into forecasting procedures where traditional methods are limited to broad, risk-free impact estimates.

Introduction

Before one can attempt to assign responsibility for a gain in energy efficiency to a particular technology or change in behavior, the aggregate gain in efficiency must be determined. Once this is accomplished, there exists a benchmark of the past with which to forecast future outcomes. The first part of this paper outlines the underlying analysis in estimating the scope of energy saved at a food processing plant before the June 2006 and 2007 freezing and canning seasons. As the facility in question did not implement capital improvement projects during the estimation time frame, the procedures described in this paper estimate an upper bound savings calculation that can be attributed to behavior changes implemented at this facility in the form of modifications to operations and maintenance (O&M). Finally, the last section of this paper details the methodology involved in forecasting possible future savings based on the institution of similar behavioral changes. Because of confidentiality agreements, the plant management asked that the facility's name and specific type of product not be referenced in this paper.

The particular plant in question is a facility that cans and freezes a variety of vegetables. Product arrives at the plant and is sent first through a process called blanching. Blanching is a type of cleaning process where the raw vegetables are boiled to remove impurities. This process is powered solely by natural gas.

From here, the vegetables are transported to either a canning and storage process or a freezing, packaging and freezer storage process. Freezing is done by moving the vegetables through a series of freeze tunnels to where they are ultimately stored in a refrigeration storage unit. It is important to note that refrigeration is powered solely by electricity. From the production data given by the facility in question, for every 1 pound of canned goods produced there are 7 pounds of frozen vegetables produced. Summary statistics for the 2004, 2005 and 2006 production seasons are shown in Table 1 - Table 4.

Table 1: Total Production, Frozen lbs.

Production Season	Mean	S.D.
2005	701,914	409,968
2006	726,378	451,201
2007	712,944	447,776

Table 2: Total Production, Canned lbs.

Production Season	Mean	S.D.
2005	134,023	68,321
2006	98,988	63,930
2007	91,742	55,396

Table 3: Total Therms/day

Production Season	Mean	S.D.
2005	5,142	2,183
2006	4,699	2,351
2007	4,165	2,073

Table 4: **Total kWh/day**

Production Season	Mean	S.D.
2005	111,084	44,611
2006	108,118	48,715
2007	98,266	48,273

Modifying Behavior

It is the belief of the Industrial Efficiency Alliance (IEA) and the Northwest Energy Efficiency Alliance (NEEA) that a gain in energy efficiency was made as the result of certain behavior/O&M changes implemented at the plant before the 2006 growing season, and once again, before the 2007 production season. These behavioral efficiency measures include a series of process changes made by production personnel aimed at curtailing boiler, refrigeration and air compressor equipment usage.

The first behavioral measure instituted at the facility involves the monitoring of employee practices. In a first step, the facility management assigned the role of an energy manager to key staff members. This person's role is to monitor the energy use of production personnel with the goal of increasing employee awareness. Additionally, weekly energy meetings take place at the facility and serve as a mechanism to increase energy awareness, identify opportunities for efficiency and track the firm's progress toward energy savings goals.

Unlike distinct capital projects, behavior change measures do not have easily defined measure boundaries short of the whole facility. As a result, much of the impact of a behavior change intervention is not susceptible to submetering. To provide examples, rather than an exhaustive list, however, the following paragraphs provided specific instances of the actions that derive from the energy team's meetings:

1) Production staff identified savings opportunities in their spraying system. Compressed air is used in the facility to move vegetable sprayers back and forth along the production line. One of the mechanics on site developed a way to reuse compressed air rather than exhaust it after it has powered a sprayer. This new procedure connects the exhaust line of a single sprayer to the next sprayer in sequence (there are around 100 sprayers in the plant). In this manner, the exhaust of the first sprayer powers the next sprayer saving the expenditure of additional compressed air.

2) The maintenance manager and head electrician of the facility determined that too many floor heaters were running in the cold storage facility. Out of 36 total heaters, they determined twelve could be manually shut of without affecting employee work conditions. As these heaters normally ran all the time, reducing their collective operating time was a simple measure to implement.

3) Facility staff determined that significant opportunities existed in monitoring boilers used in the vegetable blanching process. Management found that boilers normally remained on even when not in use. Manufacturing staff simply instituted a policy that boilers would be turned off when not in use. This occurred mostly during break and lunch hours and amounted to turning the boilers off up to three hours a day.

Model Estimation

The first task in the savings estimation involved analyzing energy use, weather and production data supplied by the manufacturing staff at the facility. This was done using two linear models, one for kWh and one for Therms. These models identify those factors having the greatest influence on energy use at the plant. The models presented in this paper provide an efficient way to combine data on factors that may be influencing energy use at the facility and determine if the per day energy consumption is increasing, decreasing or remaining the same between years. Again, the resulting calculations provide an upper bound estimate that controls for variations in weather and production flows. Additionally, the effect of a change in the price of electricity is ruled out in the model. In this case, the facility's response to price changes is inelastic due to the perishable nature of inputs (production could not be put off to take advantage of more favorable prices) and market structure (delivery commitments were a higher priority than minimizing energy costs).

In the development of these models, both linear and quadratic terms for production, HDD, and CDD were tested. An additional variable, FREEZE, was developed to estimate the effect of temperature on the freezing of vegetables. This variable is defined as the absolute difference between outdoor temperature and freezer temperature (20^0). Based on t-tests, overall goodness of fit, collinearities, serial correlations, and model error structures the most parsimonious models were selected. Coefficients for each of the frozen vegetable products in each model are expressed in terms of lbs./energy source (kWh or therms) and coefficients for the fixed energy usage and dummy variables in each model are expressed in terms of the energy source/day. The coefficients for CDD, HDD and FREEZE are expressed in energy source/degree Fahrenheit.

kWh Model

The data used for the kWh savings model is from the Industrial Efficiency Alliance Tracking System. This data contains both kWh and Therms energy consumption information allowing for the estimation of both a natural gas savings equation and electricity savings equation. The sample for each year is shown in Table 5.

Table 5: KWH Model Sample

Year	Days of Production
2005	120
2006	116
2007	124
Total Sample	**N=360**

The kWh savings model specification is defined as follows:

$$KWH = \alpha_{2005} + \alpha_{2006} + \alpha_{2007} + \beta' FREEZE_i + \beta' PROD_i + (\alpha_{2005} \times FREEZE) + (\alpha_{2006} \times FREEZE) + (\alpha_{2007} \times FREEZE) + \varepsilon_i$$

$KWH =$ *Facility daily energy use in kWh*

$\alpha_{2005} =$ *Constant term indicating daily energy savings for* 2005

$\alpha_{2006} =$ *Constant term indicating daily energy savings for* 2006

$\alpha_{2007} =$ *Constant term indicating daily energy savings for* 2007

$FREEZE =$ *Vector of variables describing the absolute difference between outdoor temparture and freezer temperature* (20^o)

$PROD =$ *Vector of variables describing the amount and type of product produced on each day*

$\alpha_{2005} \times FREEZE =$ *Interaction term describing the marginal effect of freezing on energy use in* 2005

$\alpha_{2006} \times FREEZE =$ *Interaction term describing the marginal effect of freezing on energy use in* 2006

$\alpha_{2007} \times FREEZE =$ *Interaction term describing the marginal effect of freezing on energy use in* 2007

$i =$ *Index for day of production*

$\varepsilon =$ *Error term asummed normally distributed*

$\alpha, \beta =$ *Coefficients to be estimated*

The specific variables used in the final model specification are described in Table 6.

Table 6: KWH Model Variable Definitions

Variable Name	Units	Description
D_{2006}	kWh/day	kWh Energy savings, 2006
D_{2007}	kWh/day	kWh Energy savings, 2007
FREEZE	Degrees	Difference between freezer temperature and outdoor temperature
FroCrop1Swing	lbs.	Crop1, frozen, produced by the swing shift
FroCrop1Grav	lbs.	Crop1, frozen, produced by the graveyard shift
FroCrop2Day	lbs.	Crop2, frozen, produced by the day shift
FroCrop2Swing	lbs.	Crop2, frozen, produced by the swing shift
FroCrop2Grav	lbs.	Crop2, frozen, produced by the graveyard shift
FroCrop3Day	lbs.	Crop3, frozen, produced by the day shift
FroCrop3Grav	lbs.	Crop3, frozen, produced by the graveyard shift
FroCrop4Day	lbs.	Crop4, frozen, produced by the day shift
FroCrop4Swing	lbs.	Crop4, frozen, produced by the swing shift
FroCrop4Grav	lbs.	Crop4, frozen, produced by the graveyard shift
FroCrop5Day	lbs.	Crop5, frozen, produced by the day shift
FroCrop5Swing	lbs.	Crop5, frozen, produced by the swing shift
FroCrop5Grav	lbs.	Crop5, frozen, produced by the graveyard shift
CanCrop1Day	lbs.	Crop1, canned, produced by the day shift
CanCrop2Day	lbs.	Crop2, canned, produced by the day shift
CanCrop3Grav	lbs.	Crop3, canned, produced by the graveyard shift
D_{2006} FREEZE	Degrees	Marginal effect of product freezing on energy use for 2006
D_{2007} FREEZE	Degrees	Marginal effect of product freezing on energy use for 2007

kWh Model Estimation Results

The estimation results from the kWh savings model are given in Table 7. An F test yields a test statistic of 596.16 with 21 degrees of freedom, indicating that the model has significant explanatory power. The coefficients for 2006 and 2007 energy savings are both negative suggesting that each year shows an increase in energy efficiency, or a decrease on average in daily energy use with respect to kWh. The variables D_{2006} suggests 2006 used 10,472.1 kWh/day less than 2005 while the variable D_{2007} suggests 2007 used 28,704.8 kWh/day less than 2005. The marginal rates of energy use per pound of product are all visible in Table 7 and significant at 1 percent.

The marginal effects of product freezing on energy use for 2006 and 2007 are illustrated by the interaction variables D_{2006} FREEZE and D_{2007} FREEZE respectively. In 2006, for every degree above 20 degrees an additional 171.88 kWh is required by the refrigeration system to maintain product temperature. For 2007, every degree above 20 degrees requires an additional 462.53 kWh by the refrigeration system.

Table 7: KWH Model Estimation Results

Variable Name	Coefficient Estimate	Standard Error	Significance Level
Constant	21,190.1	4957.4	
D_{2006}	-10,472.1	5861.6	8%
D_{2007}	-28,704.8	5965.3	<1%
FREEZE	321.5	116.8	<1%
FroCrop1Swing	0.13	0.03	<1%
FroCrop1Grav	0.12	0.03	<1%
FroCrop2Day	0.10	0.01	<1%
FroCrop2Swing	0.12	0.01	<1%
FroCrop2Grav	0.08	0.01	<1%
FroCrop3Day	0.13	0.01	<1%
FroCrop3Grav	0.13	0.01	<1%
FroCrop4Day	0.20	0.04	<1%
FroCrop4Swing	0.11	0.01	<1%
FroCrop4Grav	0.12	0.01	<1%
FroCrop5Day	0.17	0.02	<1%
FroCrop5Swing	0.13	0.01	<1%
FroCrop5Grav	0.06	0.02	<1%
CanCrop1Day	0.34	0.09	<1%
CanCrop2Day	0.42	0.15	<1%
CanCrop3Grav	0.19	0.03	<1%
D_{2006} FREEZE	171.88	134.60	20%
D_{2007} FREEZE	462.53	136.66	<1%

Several variables were omitted as they significantly reduced the explanatory power of the model. These variables are listed in Table 8. The introduction of these variables did improve the model's performance.

Table 8: Omitted Variables

Variable Name	Units	Description
FroCrop1Day	lbs.	Crop1, frozen, day shift
FroCrop3Swing	lbs.	Crop3, frozen, swing shift
CanCrop1Swing	lbs.	Crop1, canned, swing shift
CanCrop1Grav	lbs.	Crop1, canned, graveyard shift
CanCrop2Swing	lbs.	Crop2, frozen, swing shift
CanCrop2Grav	lbs.	Crop2, canned, graveyard shift
CanCrop3Day	lbs.	Crop3, canned, day shift
CanCrop3Swing	lbs.	Crop3, canned, swing shift

Therms Model

The same data used to estimate the kWh savings model were used to estimate the Therms savings model. This model attempts to capture the year-to-year change in energy use surrounding the blanching of vegetables as this process is powered solely by natural gas.

The Therms savings model specification is defined as follows:

$$THERMS = \alpha_{2005} + \alpha_{2006} + \alpha_{2007} + \beta' CDD_i + \beta' PROD_i + e_i$$

$THERMS =$ *Facility daily natural gas use in therms*

$\alpha_{2005} =$ *Constant term indicating daily energy savings for* 2005

$\alpha_{2006} =$ *Constant term indicating daily energy savings for* 2006

$\alpha_{2007} =$ *Constant term indicating daily energy savings for* 2007

$CDD =$ *Cooling Degree Days. Vector of variables describing the difference between outdoor temparture and ambient room temperature* (65^o) *when outdoor temperature is greater than ambient room temperature*

$PROD =$ *Vector of variables describing the amount and type of product produced on each day*

$i =$ *Index for day of production*

$e =$ *Error term asummed normally distributed*

$\alpha, \beta =$ *Coefficients to be estimated*

The specific variables used in the final model specification are described in Table 9.

Table 9: Therms Model Variable Definitions

Variable Name	Units	Description
D_{2006}	Therms/day	Natural Gas Energy savings, 2006
D_{2007}	Therms/day	Natural Gas Energy savings, 2007
CDD	Degrees	Cooling degree days
FroCrop1Swing	lbs.	Crop1, frozen, produced by the swing shift
FroCrop2Day	lbs.	Crop2, frozen, produced by the day shift
FroCrop2wing	lbs.	Crop2, frozen, produced by the swing shift
FroCrop2Grav	lbs.	Crop2, frozen, produced by the graveyard shift
FroCrop3Day	lbs.	Crop3, frozen, produced by the day shift
FroCrop3Grav	lbs.	Crop3, frozen, produced by the graveyard shift
FroCrop4Day	lbs.	Crop4, frozen, produced by the day shift

FroCrop4Swing	lbs.	Crop4, frozen, produced by the swing shift
FroCrop4Grav	lbs.	Crop4, frozen, produced by the graveyard shift
FroCrop5Day	lbs.	Crop5, frozen, produced by the day shift
FroCrop5Swing	lbs.	Crop5, frozen, produced by the swing shift
FroCrop5Grav	lbs.	Crop5, frozen, produced by the graveyard shift
CanCrop1Day	lbs.	Crop1, canned, produced by the day shift
CanCrop1Swing	lbs.	Crop1, canned, produced by the swing shift
CanCrop1Grav	lbs.	Crop1, canned, produced by the graveyard shift
CanCrop2Day	lbs.	Crop2, canned, produced by the day shift
CanCrop2wing	lbs.	Crop2, canned, produced by the swing shift
CanCrop3Day	lbs.	Crop3, canned, produced by the day shift
CanCrop3Swing	lbs.	Crop3, canned, produced by the swing shift
CanCrop3Grav	lbs.	Crop3, canned, produced by the graveyard shift

Therms Model Estimation Results

The estimation results from the Therms savings model are given in Table 10. An F test yields a test statistic of 353.09 with 23 degrees of freedom, indicating that the model has significant explanatory power. The coefficients for 2006 and 2007 energy savings are both negative suggesting that each year shows an increase in energy efficiency, or a decrease on average in daily energy use with respect to Therms. The variables D_{2006} suggests 2006 used 119.9 Therms/day less than 2005 while the variable D_{2007} suggests 2007 used 512.6 Therms/day less than 2005.

The marginal rates of energy use per pound of product are all visible in Table 10. Every marginal rate of natural gas usage per pound of product is significant at 10 percent. The variable CDD explains the effect of weather on the blanching process and is significant at 2 percent. The coefficient of CDD suggests that for every degree above ambient room temperature the blanching process requires 20 Therms less to raise the vegetables to the appropriate temperature.

Table 10: Therms Model Estimation Results

Variable Name	Coefficient Estimate	Standard Error	Significance Level
Constant	1,278.2	79.1	
D_{2006}	-119.9	66.1	7%
D_{2007}	-512.6	67.9	<1%
CDD	-20.2	8.2	2%
FroCrop1Swing	0.0075	0.001	<1%
FroCrop2Day	0.005	0.0006	<1%
FroCrop2wing	0.004	0.0008	<1%
FroCrop2Grav	0.003	0.0006	<1%
FroCrop3Day	0.005	0.0007	<1%
FroCrop3Grav	0.006	0.0007	<1%
FroCrop4Day	0.005	0.0021	1%
FroCrop4Swing	0.003	0.0007	<1%
FroCrop4Grav	0.005	0.0007	<1%
FroCrop5Day	0.007	0.0012	<1%
FroCrop5Swing	0.005	0.0007	<1%
FroCrop5Grav	0.005	0.001	<1%
CanCrop1Day	0.02	0.006	<1%

CanCrop1Swing	0.01	0.006	5%
CanCrop1Grav	0.03	0.007	<1%
CanCrop2Day	0.02	0.02	8%
CanCrop2wing	0.04	0.01	<1%
CanCrop3Day	0.01	0.003	<1%
CanCrop3Swing	0.01	0.004	<1%
CanCrop3Grav	0.01	0.003	<1%

Several variables were also omitted from this model as they significantly reduced its explanatory power. These omitted variables are listed in Table 11. Additionally, the interaction of CDD and the annual energy savings variables was tested and dropped from the final model specification. The introduction of these variables did not improve the model's performance.

Table 11: Omitted Variables

Variable Name	Units	Description
FroCrop1Day	lbs.	Crop1, frozen, day shift
FroCrop1Grav	lbs.	Crop1, frozen, graveyard shift
FroCrop3Swing	lbs.	Crop3, frozen, swing shift
CanCrop2Grav	lbs.	Crop2, canned, graveyard shift

Monte Carlo Simulation: Energy Savings Simulation and Forecasting Methodology

In order to quantify and forecast the range of potential future savings a Monte-Carlo simulation was used to address production and weather uncertainty. This process is best used to calculate a simulated mean energy savings between years derived from a normal distribution of energy, production and temperature data. Additionally and just as important, this simulation also calculates a distribution of potential savings. This is the advantage gained over a single point forecast.

With the estimation of each of the kWh and Therms models complete, and given the assumption of normally distributed production and temperature data occurring at the plant, we can simulate production in each year subject to a random mix of energy use, production and temperature possibilities. Although random, these combinations still follow the true stochastic behavior of each variable as experienced by the facility during the 2005, 2006 and 2007 production seasons.

The kWh and Therms equations estimated above are used to generate a normal distribution for each of the variables in both models. These distributions are built by first generating and randomly selecting data for each of the variables, substituting these variables into the estimated equations and then performing a second estimation to obtain coefficients for each variable. Each resulting coefficient is then stored to build a distribution of potential outcomes. This process is repeated 5000 times in order to build the simulated distributions.

The distributions of most interest are those for the variables D_{2006} and D_{2007} in both models as the means of these distributions yield the simulated mean energy savings for each year. When the distributions are complete, the mean and standard distribution of each distribution (for both models) is calculated to determine a range of future savings possibilities given changes in production, temperature and energy use. If the coefficients for D_{2006} and D_{2007}

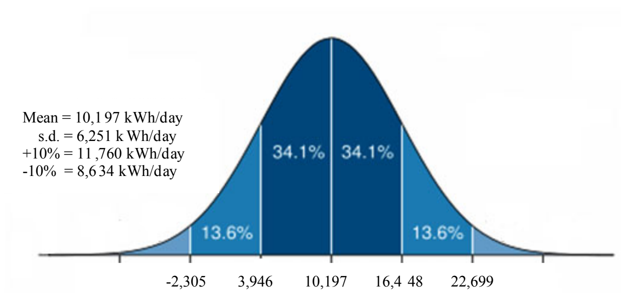
are negative after 1 of the 5000 simulations, the result is a savings in energy use. If positive, the opposite is true.

Because of the variations inherent in the data used for the simulation, not every simulated coefficient for savings comes out negative. The simulation results explained in the next section show that regardless of the behavior changes instituted at the facility, certain combinations of production and temperature will crowd out behavioral energy efficiency measures.

Simulation Results

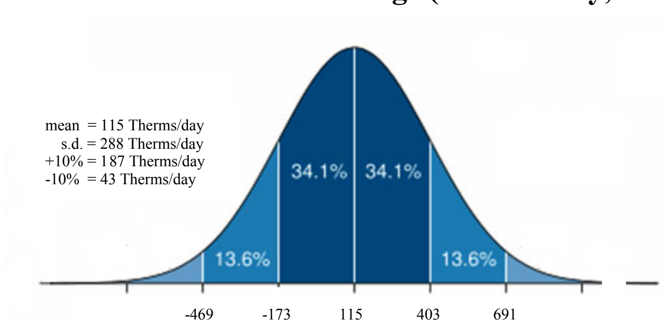
As a result of the Monte-Carlo simulation process, the first savings distribution shown in Figure 1 was calculated. This distribution yields a mean savings of 10,197 kWh/day with a standard distribution of 6,251 kWh/day. The resulting simulation also shows that repeating the same behavioral changes made between the 2005 and 2006 production seasons will result in a daily energy savings between 3,946 kWh/day and 16,488 kWh/day 68.2% of the time. Figure 1 also shows that 60% of the outcomes will result in a savings of up to 11,760 kWh/day. As previously described, the simulation does result in a negative savings. However, this will occur less than 15% of the time.

Figure 1: 2006 Electricity Savings (kWh/day, Simulated)



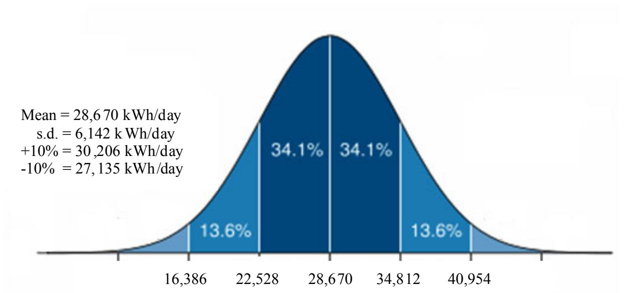
The results of the second simulation for gas savings are visible in Figure 2. This simulation results in an average daily savings of 115 Therms. Because of the simulated standard distributions and potential fluctuations in production and temperature, negative savings are possible again given the measures implemented at the facility between 2005 and 2006. The simulation shows that these negative savings are possible nearly 40% of the time.

Figure 2: 2006 Natural Gas Savings (Therms/day, Simulated)



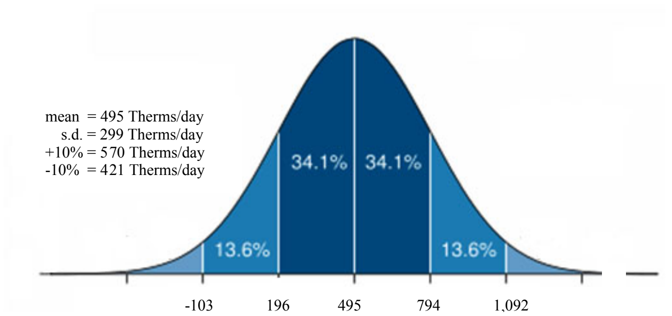
Simulation results for kWh daily savings between 2006 and 2007 are shown in Figure 2. This simulation resulted in positive energy savings in each of the 5000 calculations. The results show that energy savings of up to 30,206 kWh/day are possible 60% of the time.

Figure 3: 2007 Electricity Savings (kWh/day, Simulated)



Finally, the results of the last simulation for gas savings are visible in Figure 4. This simulation shows the potential for gas savings given the same measures instituted at the facility between the 2006 and 2007 manufacturing season. Again, Figure 4 shows that negative savings are possible. However, with an estimated daily savings of 495 Therms and a standard distribution of 299 Therms/day, negative savings occur less than 15% of the time.

Figure 4: 2007 Natural Gas Savings (Therms/day, Simulated)



Conclusion

The role of assigning responsibility for efficiency gains is at this point for the firm an open discussion. Estimation is useful in determining an upper bound of energy savings as a result of behavioral modifications while simulation can provide clarity in understanding the degree to which uncertainty will effect these savings. The results of the estimation show that the 2006 and 2007 production seasons were more energy efficient compared to 2005 while the simulation results show that certain combinations of production and temperature, if extreme enough, can cancel out these energy savings. Finally, the extent to which behavioral measures implemented at the facility can take credit for these estimated savings is unclear. However, once a model controlling for fluctuations in production and temperature is developed, the most common variables causing distortions in perceived efficiency gains are silenced.