Center for Advanced Energy Studies

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Impact of Window Replacement on Yanke Building Energy Consumption

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From May to November of 2015, the majority of the windows in the Yanke Family Research Park (*i.e.* the Yanke Building) were removed and replaced with modern high-quality windows because many of the exiting windows had failed and fogged. While such a retrofit should result in significant energy savings, there remains a possibility that improper integration of the new window systems to the building structure may degrade performance by inadvertently providing paths for infiltration of outside air or by providing "bridges" of relatively high thermal conduction between the conditioned space and the environment. In an effort to assess the impact of the retrofit, researchers at the CAES Energy Efficiency Research Institute (CEERI) analyzed the energy consumption before and after the window retrofit, using industry standard techniques to normalize consumption to prevailing weather conditions.

CEERI
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Executive Summary

From May to November of 2015, the majority of the windows in the Yanke Family Research Park (*i.e.* the Yanke Building) were removed and replaced with modern high-quality windows because many of the exiting windows had failed and fogged. While such a retrofit should result in significant energy savings, there remains a possibility that improper integration of the new window systems to the building structure may degrade performance by inadvertently providing paths for infiltration of outside air or by providing “bridges” of relatively high thermal conduction between the conditioned space and the environment.

In an effort to assess the impact of the retrofit, researchers at the CAES Energy Efficiency Research Institute (CEERI) analyzed the energy consumption before and after the window retrofit, using industry standard techniques to normalize consumption to prevailing weather conditions.

By examining hourly electricity consumption in the building and the recorded weather conditions for a 10 month period prior to the retrofit (July 2014 through April 2015), we created a model (3 parameter change-point linear regression) to predict electricity consumption as a function of outside temperature to establish the pre-retrofit baseline. That baseline was used to predict electricity consumption for the 12 months after the retrofit (December 2015 through November 2016) which was compared to actual electricity use. A similar process was used to compare monthly natural gas consumption for the pre- and post-retrofit.

The results showed that the energy consumption (*i.e.* both electricity use and natural gas use) during the post-retrofit period was significantly higher than the energy consumption during the pre-retrofit period. For electricity, which is the driver for building cooling, this change was manifest in both the non-weather related use (6.3% higher post-retrofit) and in sensitivity of electricity consumption to outside temperature (53.1% greater post-retrofit). The goal of weatherization improvements is to make that sensitivity smaller. **When the weather normalized analysis was conducted, the total electricity use of the post-retrofit period was 10.4% higher than the model predicts for pre-retrofit building at the post-retrofit weather conditions.**

For natural gas, which is used year round, but is responsible for building space heating, the picture was not as clear, but also showed an increase of energy use. The weather normalization analysis indicated that **natural gas usage in Yanke increased by 31.8% post-retrofit.**

Energy Use Intensity (EUI) is a metric commonly used when comparing energy use between buildings. The EUI looks at year-round source energy use and divides by the building square footage, allowing a broad discussion among buildings of differing sizes. The source energy EUI was calculated using both the electricity and the natural gas use. **Pre-retrofit, the EUI was 145.0 kBtu/ft^2-yr and the projected post-retrofit, the EUI**

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is 167.1 kBtu/ft²-yr, showing an increase of 15.2% To put this in context, the median EUI for office buildings is 148.1 kBtu/ft²-yr.

It is unclear what causes the increased energy consumption. The increase in the non-weather related energy consumption indicates an increase in occupancy and plug loads, which would partially, but not completely, explain the increase. Our understanding of the physics of energy transfer in buildings leads us to believe that an increase in building occupancy and plug loads would alter the non-weather related energy use and the building balance-point temperature, but not the sensitivity of energy use to outside temperature. We have ascertained that the last major tenant to move into the building, Boise State Public Radio's broadcast studio, began full operation in April 2014, 2 months prior to our pre-retrofit baseline period.

Further analysis shows that the time of day electricity use patterns have changed somewhat, which suggests that a change in building operation (*e.g.* HVAC set-points) may have contributed to the increased energy use, but probably not enough to account for all of the difference. There is also some evidence that there may be significant periods of time when the heating and cooling systems are acting simultaneously, thus increasing consumption of both electricity and natural gas. For this to be a plausible explanation, there must have been some change in the building control set-points around the same time as the window retrofit.

The CEERI staff plans to continue this research by taking infra-red (heat sensitive) photographs of the outside of the building as the weather gets colder, thus making potential problems with the building envelope more obvious.

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Introduction

The Yanke Family Research Park (*i.e.* the Yanke Building) is a facility of Boise State University and is located at 220 E. Parkcenter Blvd., Boise, Idaho. This two-story building, of which the gross area is 84,053 ft^2, contains offices on both the first and second floors. The Boise State Public Radio administrative offices and broadcast studio occupies the west end of the building. The structure was originally built in the 1980's as the world headquarters for OreIda and Boise State assumed ownership in 2010. It was observed at that time that many of the windows had failed seals between the two panes, causing a fogging of the window and degradation of the thermal barrier. A major project to replace the windows began in May 2015 and was completed in November 2015. The replacement windows have high energy performance (*i.e.* high U-Value and lower Solar Heat Gain Coefficient (SHGC)) and were custom ordered to be compatible with the building envelope.

This report summarizes the analysis of energy consumption before and after the window retrofit using 15-minute electricity use data from the smart meter of the Idaho Power and monthly natural gas utility bill data from the Intermountain Gas Company. For the analysis, the energy data of the pre-retrofit period from July 2014 to April 2015 (10 months) and the post-retrofit period from December 2015 to November 2016 (12 months) were used. In addition, Outside Air Temperature (OAT) data from the National Weather Service (Boise Airport, NOAA, 2017)) during both the pre-retrofit and post-retrofit periods was used.

Methodology

This report used the following methods: change-point linear regression analysis, weather normalized analysis, EUI analysis, and time of day analysis. Figure 1 shows the procedures for the energy analysis, the major steps of which are summarized below:

- 15-minute interval electricity use data (kWh) and monthly natural gas utility bill data (therm[1]) during both the pre-retrofit (July 2014 to April 2015) and the post-retrofit (December 2015 to November 2016) periods were collected. The 15-minute interval electricity use data summed into hourly interval electricity use data. In addition, hourly OAT data (°F) during the corresponding periods was collected (NOAA, 2017).

[1] In this report, the unit of natural gas data was converted from therm to kWh using a factor of 29.3001.

- Missing data were filled in using linear interpolation (Long, 2006). It was found that the hourly OAT data had missing data for three hour gaps during the pre-retrofit period and two hour gaps during the post-retrofit period.
- Once the data set was set to hourly intervals and the gaps addressed, the electricity use data were further reorganized by dividing the hourly electricity use into the two categories: weekdays (WDs) and weekends/holidays (WEHs)[2]. The hourly OAT data was also categorized into the two periods. For the analysis of the monthly natural gas use, it was calculated for monthly average daily[3] natural gas use to normalize the billing periods of the monthly natural gas use. The hourly OAT data was also calculated for the monthly average daily OAT.
- Change-point linear regression analysis was conducted using the ASHRAE RP-1050 Inverse Modeling Toolkit (IMT) (Kissock et al., 2001). The IMT includes several models for evaluating building energy use data: simple and multiple linear regression models, variable-base degree-day models, and change-point linear regression models. In our approach, we used the change-point linear regressions to analyze the sensitivity of building energy consumption to OAT.

[2] Holidays were selected based on the payroll and holiday calendars of Boise State University.
[3] The monthly average daily use means the daily average of use per month.

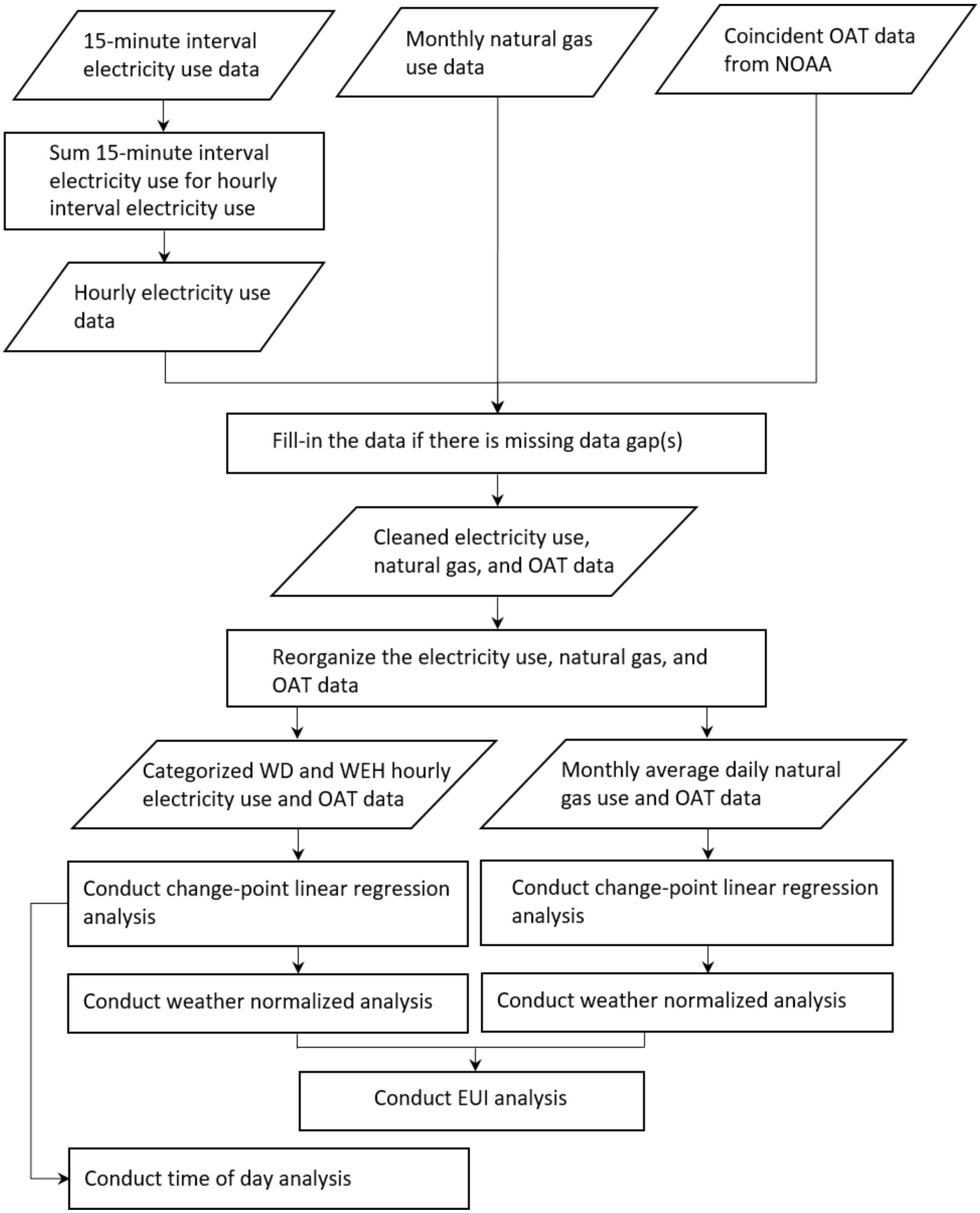


Figure 1. Procedures for the energy analysis.

There are various forms of these linear regression models as illustrated in Figure 2. Proceeding from the top to the bottom, we see the simplest model being the one parameter (1P), weather-independent regression, the one parameter being the average energy consumption which is independent of outside temperature. Next are the two parameter regression models showing linear sensitivity to outside temperature for cooling (left) and heating (right). The two parameters are the slope of the fit and the y-intercept showing the energy use that appears to be independent of outside temperature. Note that heating and cooling operations are considered separately, though there maybe overlap between the two systems in practice.

Highlighted in the center of Figure 2, we show the three parameter change-point regression models (three parameter cooling (3PC) or heating (3PH)), which are the most common approaches to weather normalization by differentiating weather-independent and weather-dependent energy use. This model captures the building 'balance-point temperature' for both heating and cooling. The balance-point temperature is the outside temperature at which the building HVAC system is not needed to maintain the desired inside temperature and recognizes the fact that internal building loads (people and equipment) in the building are equal to the building envelope heat transfer. The three parameters are the weather-independent energy use (the y-intercept of the horizontal line), the balance-point temperature, and the slope of the weather-dependent energy use (the temperature-dependent line). Other models have utility in other applications, but for the purposes of this study, these (1P, 3PC and 3PH) are the models that have proven to be useful.

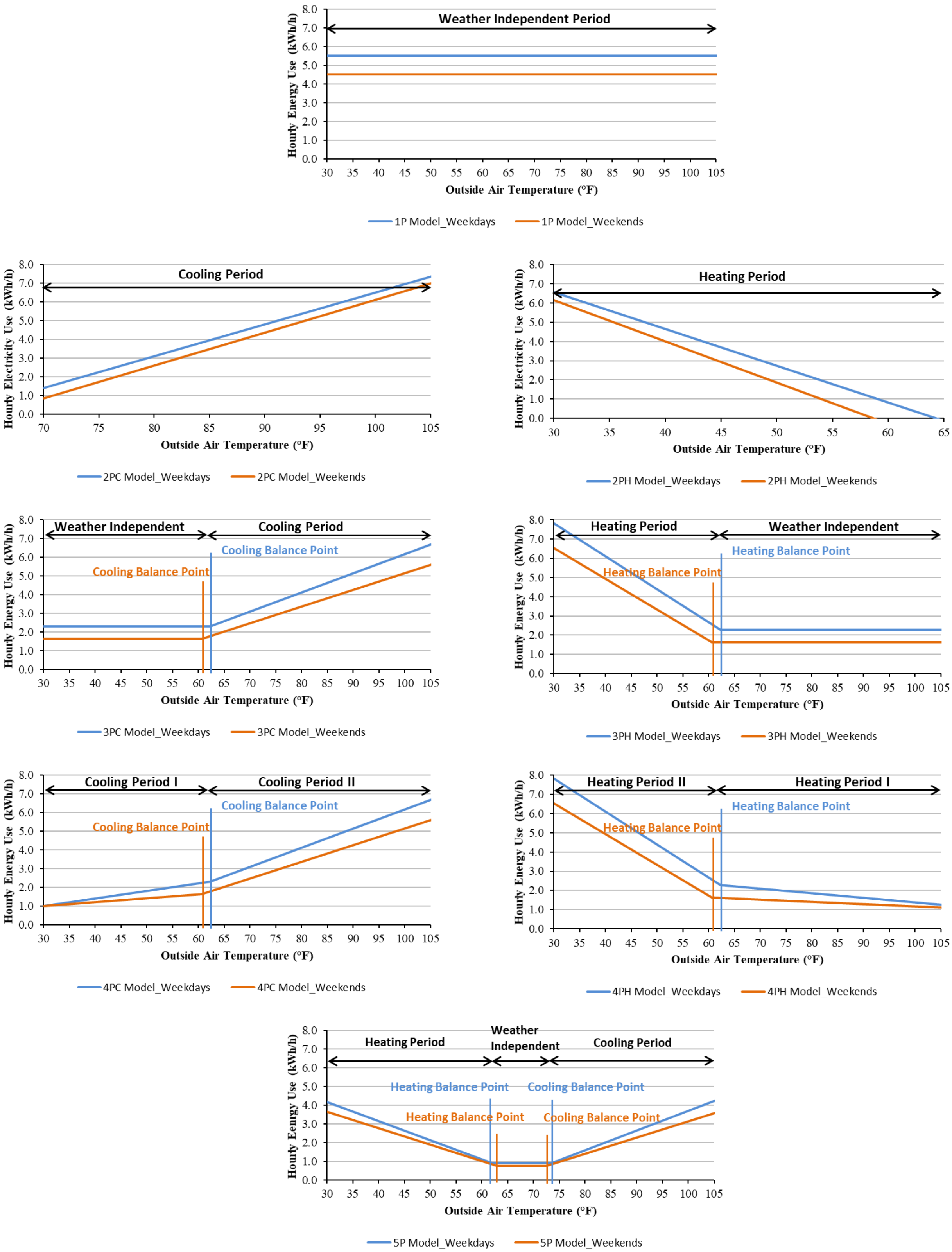


Figure 2. Examples of change-point linear regression models (Kissock et al., 2001; Oh, 2017).

The models used in this analysis, the one parameter (1P) model (*i.e.* mean model) and the three parameter cooling (3PC) or heating (3PH) linear regression models, can be defined mathematically as equations (1), (2) and (3), respectively.

$$E_{tot} = E_{w.i.} \tag{1}$$

$$E_{tot} = E_{w.i.} + CS(T_{OA} - T_{c.b.})^{+} \tag{2}$$

$$E_{tot} = E_{w.i.} + HS(T_{OA} - T_{h.b.})^{-} \tag{3}$$

Where E_{tot} is the building energy use, T_{OA} is the Outside Air Temperature (OAT), $E_{w.i.}$ is the weather-independent energy use, CS is the cooling slope that represents cooling energy use sensitivity to OAT, $T_{c.b.}$ is the cooling balance-point (change-point) temperature, HS is the heating slope that represents heating energy use sensitivity to OAT, and $T_{h.b.}$ is the heating balance-point (change-point) temperature. The notation $(\ )^{+}$ and $(\ )^{-}$ indicate that the values of the parentheses shall be zero when they are negative and positive, respectively (Kissock et al., 2003; Sever et al., 2011). In other words, the model described by equation (2) ignores temperatures colder than the cooling balance-point temperature and equation (3) ignores temperatures higher than the heating balance-point temperature.

We can also compute a standard error calculation for each coefficient (generically given as β) for the model (Kissock et al., 2001). Eq. (4) shows a functional form of the Standard Error (SE) as the difference between the true and estimated parameter values.

$$\beta_{true} = \beta_{estimated} \pm t(1 - \frac{\alpha}{2}, n - p) \sqrt{\frac{\sum_{i=1}^{n}(\hat{Y}_i - Y_i)^2}{n}} \tag{4}$$

Where t is the t statistical distribution, α is the probability[4], n is the number of data points, p is the number of the parameters, $\hat{Y}_i$ is the predicted value from the model, and Y_i is the measured value. For this analysis, ±SE gives us the range of one standard deviation of the likely value of the parameter.

[4] The assigned probability is 68%, so α is 0.34.

One of the parameters we solve for is the balance-point temperature which is the OAT at which heat gains or losses inside a building counterbalance heat losses or heat gains through the building envelope. The OAT is typically used for an independent variable of the change-point linear regression models because it is the most important explanatory variable for determining building energy use. In this report, the cooling balance-point temperatures were found for the electricity use, and the heating balance-point temperatures were found for the natural gas use. In addition, the weather-independent energy use $E_{w.i.}$ and the cooling and heating slopes (CS and HS) were found for weather-dependent electricity use and weather-dependent natural gas use, respectively.

The model parameters for the pre- and post-retrofit analysis can be directly compared, but such a comparison is insufficient to estimate the amount of energy saved due to a building retrofit because weather conditions change from year to year. To develop a clearer picture, a weather normalized analysis was conducted. In this approach, we used the model parameters of the equations (Eq. (2) and Eq. (3)) from the pre-retrofit period to estimate the energy use of the building if it had not been altered but experience the OATs of the post-retrofit period. That energy consumption can then be directly compared to the actual consumption during the post-retrofit period for an estimate of energy savings due to the retrofit.

Using the weather normalized energy consumption, EUI during the pre-retrofit period was also compared with EUI during the post-retrofit period. EUI was calculated by dividing the annual total energy use by the building gross area (Energy Star, 2017). In addition, a time of day analysis was conducted using a quartile analysis for the cooling period (Ott and Longnecker, 2010; Oh, 2017).

Results and Findings

Figures 3 is a snapshot of the hourly electricity consumption and hourly OAT for the Yanke building. Figure 4 shows the monthly average daily natural gas consumption for the same time period. The figures show the electricity and natural gas data used in the analysis as a function of time. Figure 3 clearly reflects the difference in building electricity use on weekdays and weekends/holidays while Figure 4 shows the strong seasonal dependency of natural gas use.

Electricity use analysis during pre-retrofit

As is evident from Figure 3, the electricity demand is very different on weekdays compared to weekends/holidays. Therefore, the analysis was performed on these two groups of data separately. Table 1 shows the results of the change-point linear regression models generated for the hourly electricity use during the pre-retrofit period. The 3PC model was used for the weekday data but the weekend/holiday data showed little or no sensitivity to OAT so the 1P model was the best fit. The results from the pre-retrofit analysis were that the cooling balance-point temperature was 49.62 ± 1.94°F, the sensitivity to OAT (*i.e.* Cooling Slope) was 1.60 ± 0.04 kWh/°F, and the weather-independent electricity use was 100.47 ± 0.71 kWh. For the weekends/holidays, no sensitivity to OAT was observed and the average electricity use was 72.11 kWh. These results are shown graphically on Figure 5. Note that dotted lines are used to show the range of likely values of the parameters as given by the Standard Error.

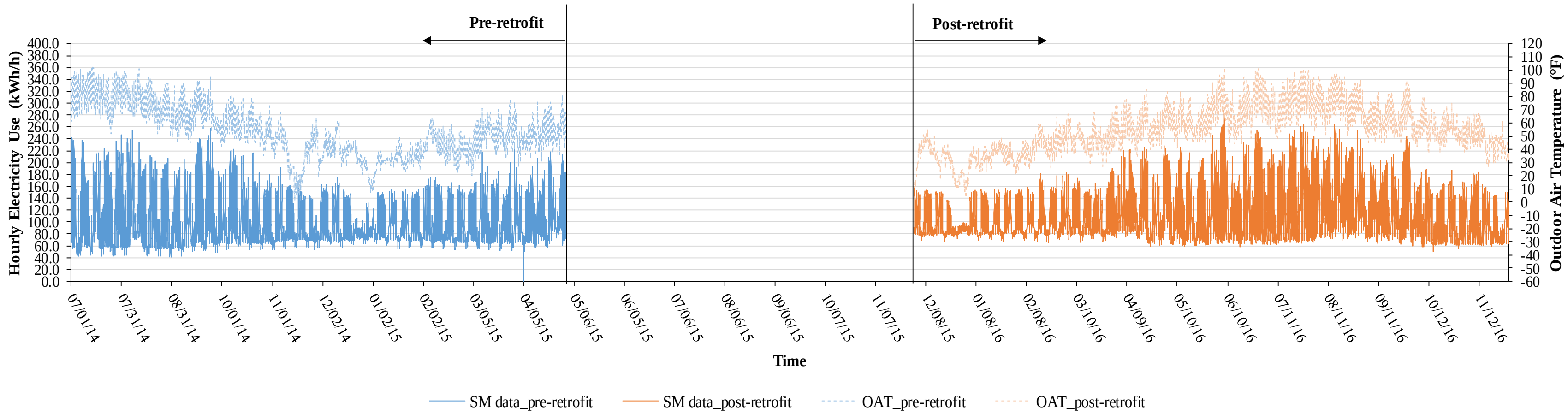


Figure 3. Time series plot for hourly electricity use and OATs for the pre-retrofit period (July 2014 to April 2015) and the post-retrofit period (December 2015 to November 2016).

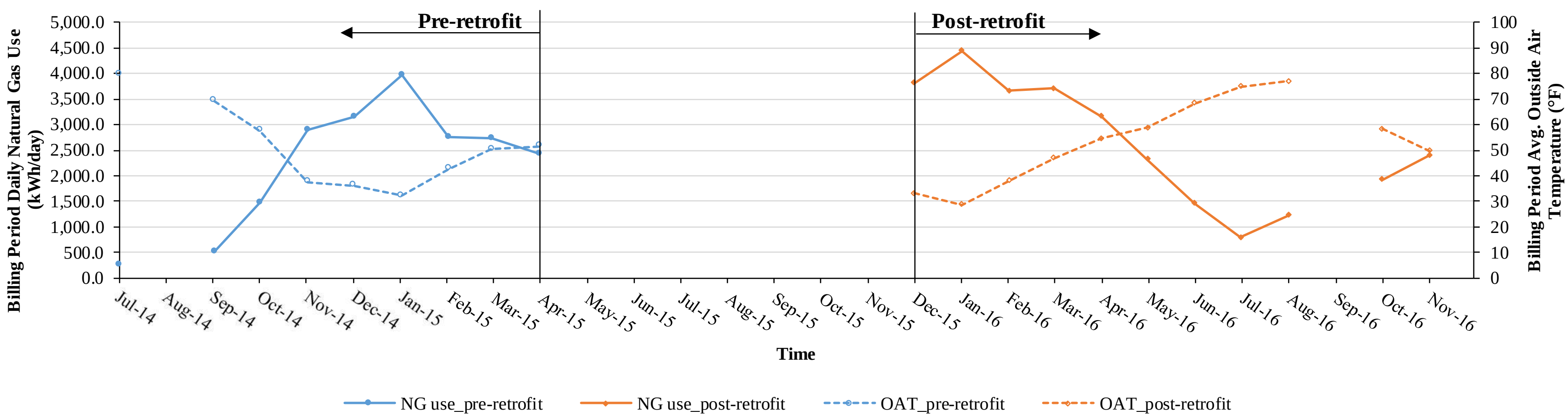
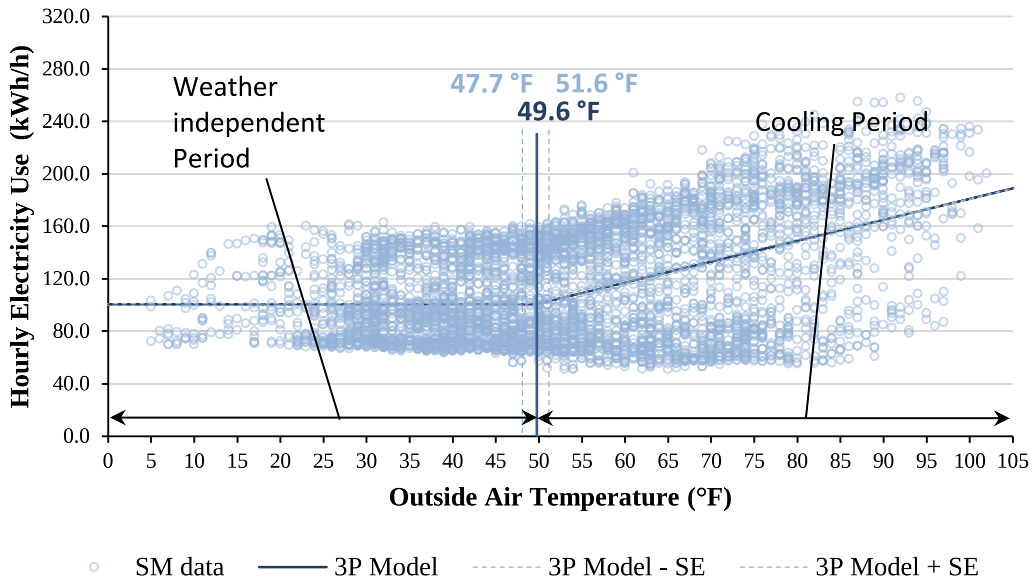


Figure 4. Time series plot[5] for monthly average daily natural gas use and OATs for the pre-retrofit billing period (July 2014 to April 2015) and the post-retrofit billing period (December 2015 to November 2016).

[5] The NG use data of August 2014 during the pre-retrofit period and September 2016 during the post-retrofit period were not available.

Table 1. 3PC and 1P linear regression model results for the pre-retrofit period.

	Cooling balance-point temperature (ºF)	Left slope (kWh/ºF)	Right slope (kWh/ºF)	Y-axis intercept (kWh)
Weekdays	49.62	0	1.60	100.47
Standard Error (SE)	1.94	0	0.043	0.71
Weekends/holidays	NA	0	0	72.11
Standard Error (SE)	NA	0	0	NA



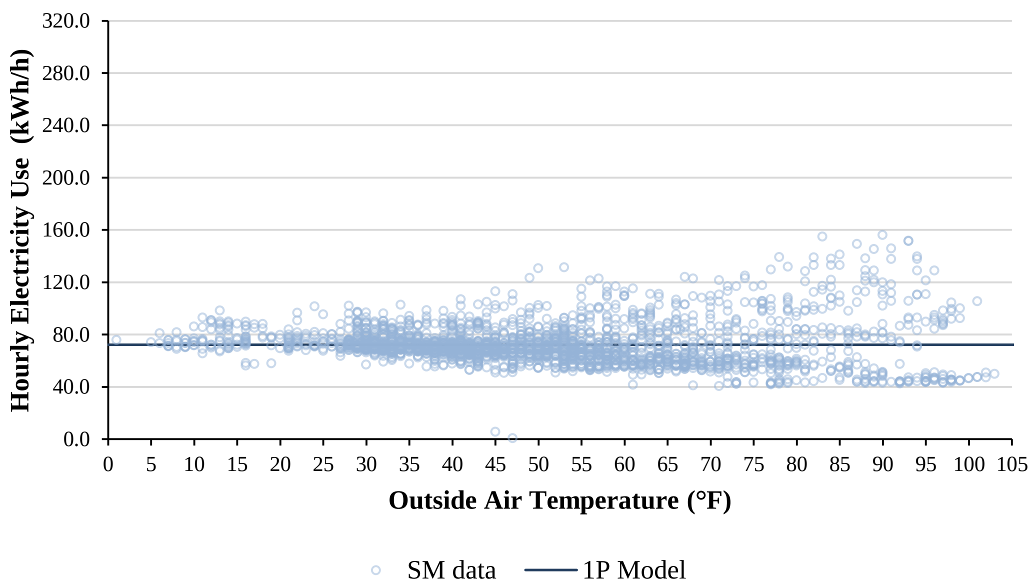


Figure 5. 3PC model with cooling balance-point temperature and its uncertainty for the weekdays (upper) and 1P model for the weekends/holidays (lower) during the pre-retrofit period (July 2014 to April 2015).

Electricity use analysis during post-retrofit

Table 2 shows the results from the change-point linear regression models generated for the hourly electricity use during the post-retrofit period. With this data set, a discernable temperature sensitivity was observed for the weekends/holidays as well, so the 3PC linear regression models were created for both weekdays and weekends/holidays. During the post-retrofit period, the cooling balance-point temperature was increased by approximately 4.6 °F (9.2%) compared to the pre-retrofit period. The sensitivity of the electricity use to OAT, the cooling slope, was 53.1% greater than the pre-retrofit period. The non-weather dependent portion increased by only 6.3%, indicating an increase in building occupancy or energy use patterns during the post-retrofit period[6].

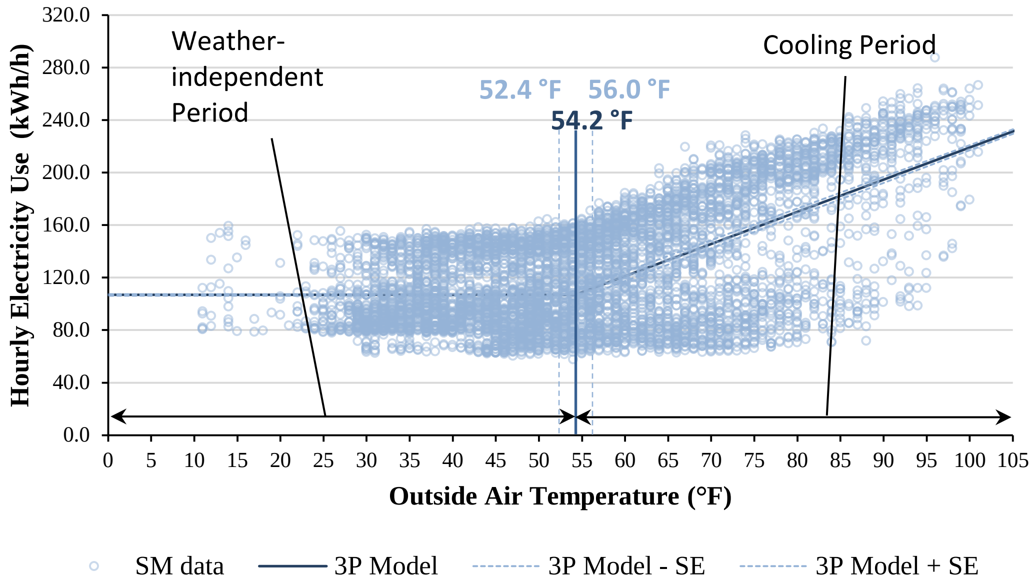
The weekend/holiday electricity use during the post-retrofit period showed less temperature sensitivity when compared to the weekday use (less than half) but it should be pointed out that the weekend/holiday electricity use pre-retrofit showed no sensitivity to OAT. All the standard errors were similar pre- and post-retrofit, indicating that the variability of the two data sets around the regressions was similar.

Table 2. 3PC linear regression model results for the post-retrofit period.

	Cooling balance-point temperature (ºF)	Left slope (kWh/ºF)	Right slope (kWh/ºF)	Y-axis intercept (kWh)
Weekdays	54.20	0	2.45	106.83
SE	1.80	0	0.041	0.57
Weekends/holidays	53.92	0	1.10	78.44
SE	1.92	0	0.032	0.41

Figure 6 shows the post-retrofit regressions graphically, indicating 3PC models with cooling balance-point temperatures and their uncertainty for the weekdays (upper) and the weekends/holidays (lower).

[6] The weekday models between the pre- and post-retrofit periods were compared without the weekend/holiday models because the weekend/holiday model pre-retrofit did not have a cooling balance-point temperature.



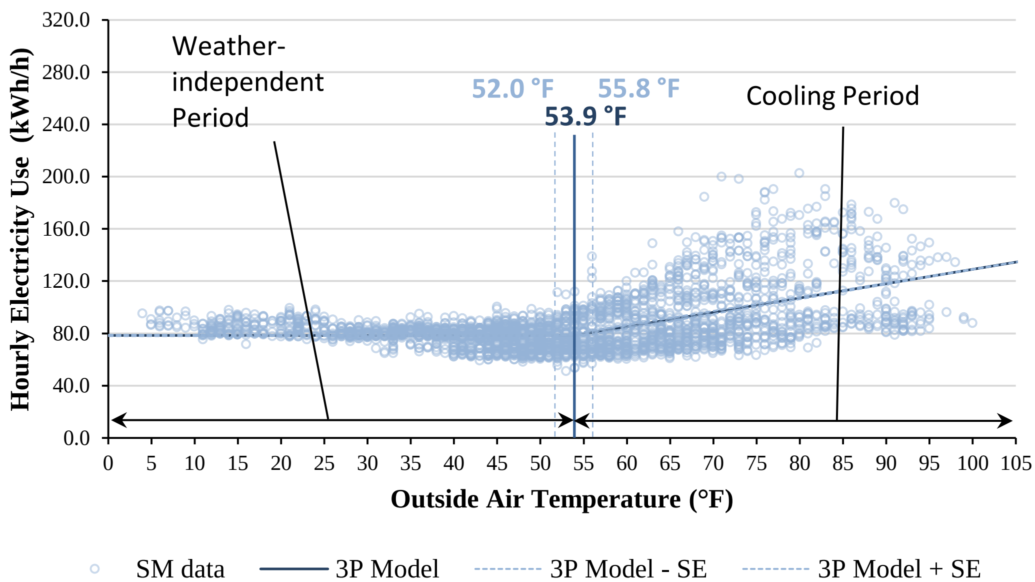


Figure 6. 3PC models with cooling balance-point temperatures and their uncertainty for the weekdays (upper) and the weekends/holidays (lower) during the post-retrofit period (December 2015 to November 2016).

Weather normalized analysis for electricity use

To quantify and compare the electricity consumption before and after the window retrofit, a weather normalized analysis was conducted. The measured hourly electricity use during the post-retrofit period was compared with the hourly electricity use predicted by baseline models (*i.e.* the change-point linear regression models from the pre-retrofit period) using the OATs during the post-retrofit period, allowing a head-to-head comparison of the consumption data. Table 3 shows the differences between the measured and the predicted electricity use by month[7]. The highest increase of 15.8% occurred in April 2016 when the OAT was 56 ºF, and the lowest increase of 4.8% occurred in October 2016 when the OAT was 55 ºF. **Normalized for changes in weather conditions, we conclude that electricity use during the post-retrofit period was 10.4% higher than the pre-retrofit period.**

Table 3. Measured electricity use during the post-retrofit period compared to the predicted electricity use from the baseline models during the pre-retrofit period.

	Month	From	To	No. of Days	Avg. OAT	Measured (kWh/day)	Baseline (kWh/day)	Diff. (kWh/day)	Diff. (%)
Pre-retrofit period	Jul-14	7/1/14	7/31/14	31	82	2,655			
	Aug-14	8/1/14	8/31/14	31	76	2,636			
	Sep-14	9/1/14	9/30/14	30	67	2,623			
	Oct-14	10/1/14	10/31/14	31	57	2,520			
	Nov-14	11/1/14	11/30/14	30	36	2,235			
	Dec-14	12/1/14	12/31/14	31	37	2,269			
	Jan-15	1/1/15	1/31/15	31	31	2,278			
	Feb-15	2/1/15	2/28/15	28	43	2,331			
	Mar-15	3/1/15	3/31/15	31	50	2,421			
	Apr-15	4/1/15	4/30/15	30	51	2,550			
Total						24,518			
Post-retrofit period	Dec-15	12/1/15	12/31/15	31	32	2,373	2,106	266	13%
	Jan-16	1/1/16	1/31/16	31	33	2,413	2,148	265	12%
	Feb-16	2/1/16	2/29/16	29	40	2,504	2,217	286	13%
	Mar-16	3/1/16	3/31/16	31	47	2,596	2,287	309	14%
	Apr-16	4/1/16	4/30/16	30	56	2,810	2,426	384	16%
	May-16	5/1/16	5/31/16	31	61	2,731	2,510	221	9%
	Jun-16	6/1/16	6/30/16	30	72	3,049	2,903	146	5%
	Jul-16	7/1/16	7/31/16	31	76	3,069	2,841	227	8%
	Aug-16	8/1/16	8/31/16	31	75	3,359	2,943	416	14%
	Sep-16	9/1/16	9/30/16	30	64	2,926	2,602	324	12%
	Oct-16	10/1/16	10/31/16	31	55	2,447	2,335	112	5%
	Nov-16	11/1/16	11/30/16	30	46	2,363	2,231	132	6%
Total						32,638	29,550	3,088	10%

Natural gas use analysis during pre- and post-retrofit

[7] Table 3 shows monthly average daily electricity use. This can be compared with monthly average daily natural gas use in Table 5.

A similar analysis was carried out for natural gas consumption, but since monthly billing data was the only available data, the results were much coarser and perhaps less reliable.

Using the same change-point linear regression analysis method, three parameter heating (3PH) linear regression models were created for the monthly average daily natural gas use data. Table 4 shows the results of the 3PH models generated for the pre-retrofit billing period and the post-retrofit billing period.

Table 4. 3PH linear regression model results for the pre-retrofit and post-retrofit billing periods.

	Heating balance-point temperature (ºF)	Left slope (kWh/ºF)	Right slope (kWh/ºF)	Y-axis intercept (kWh)
Pre-retrofit period	75.04	-80.76	0	244.37
SE	0.95	7.34	0	209.06
Post-retrofit period	75.16	-72.42	0	1050.54
SE	0.97	7.66	0	203.28

The results of this analysis were more difficult to interpret. Most noticeable was that the weather-independent natural gas use was over 4 times higher post-retrofit. It is our understanding that domestic hot water is provided by electric water heaters, there is no reasonable explanation for this increase. On the other hand, the slight decrease in the heating slope might be due to the improved weatherization effect of the new windows. It is also possible that the lower slope post-retrofit was a numerical artifact due to the very large baseline (weather-independent) number skewing the data.

Figure 11 shows the 3PH models with the heating balance-point temperatures during the pre-retrofit period and the post-retrofit period, respectively.

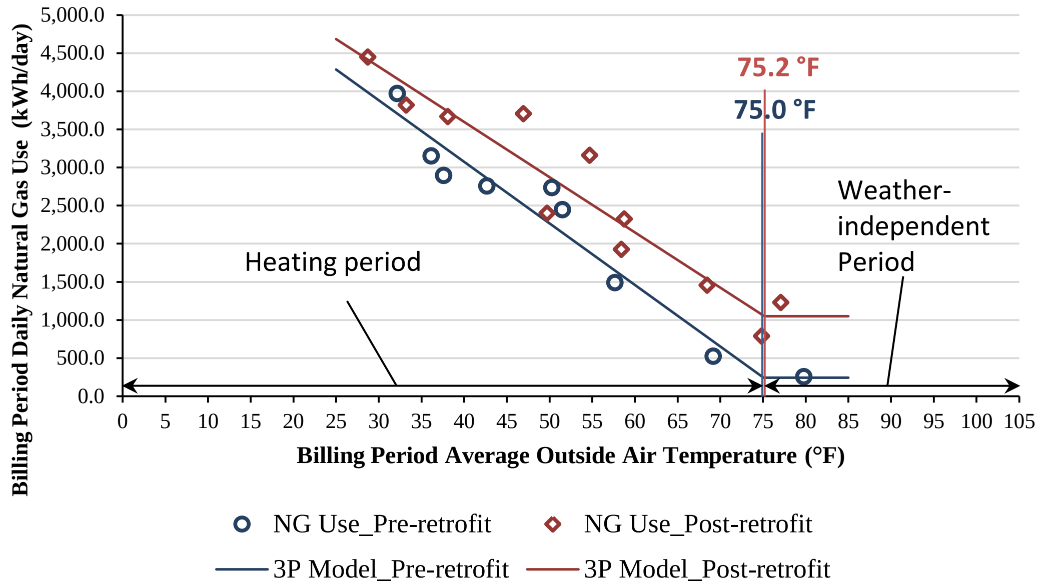


Figure 7. 3PH models with the heating balance-point temperatures and their uncertainty during the pre-retrofit billing period (July 2014 to April 2015) and the post-retrofit billing period (December 2015 to November 2016).

Weather normalized analysis for natural gas use

The weather normalized analysis was also conducted for the monthly average daily natural gas use to quantify and compare the natural gas consumption before and after the window retrofit. The measured, monthly average daily natural gas use was compared with the predicted natural gas use from the baseline model (*i.e.* the 3PH model) during the pre-retrofit billing period, using the monthly average daily OATs during the post-retrofit billing period. Table 5 shows the differences between the measured and the predicted, baseline natural gas use by the utility billing period. The highest increase of 403.2% occurred in August 2016 when the OAT was 77 ºF, and the lowest increase of 4.8% occurred in November 2016 when the OAT was 50 ºF. **The total natural gas use during the post-retrofit billing period was 31.8% higher than the pre-retrofit billing period.**

Table 5. Natural gas during the post-retrofit billing period compared to the natural gas use from the baseline model during the pre-retrofit billing period.

	Month	From	To	No. of Days	Avg. OAT	Measured (kWh/day)	Baseline (kWh/day)	Diff. (kWh/day)	Diff. (%)
Pre-retrofit period	Jul-14	6/27/14	7/28/14	32	80	255			
	Aug-14	-	-	-	-	-			
	Sep-14	8/28/14	9/26/14	30	69	524			
	Oct-14	9/27/14	10/27/14	31	58	1,487			
	Nov-14	10/28/14	12/2/14	36	38	2,894			
	Dec-14	12/3/14	1/2/15	31	36	3,150			
	Jan-15	1/3/15	1/30/15	28	32	3,967			
	Feb-15	1/31/15	3/2/15	31	43	2,754			
	Mar-15	3/3/15	3/30/15	28	50	2,734			
	Apr-15	3/31/15	4/29/15	30	52	2,444			
Total						20,210			
Post-retrofit period	Dec-15	11/21/15	12/22/15	32	33	3,815	3,620	195	5%
	Jan-16	12/23/15	1/22/16	31	29	4,445	3,985	460	12%
	Feb-16	1/23/16	2/23/16	32	38	3,667	3,226	441	14%
	Mar-16	2/24/16	3/24/16	30	47	3,705	2,511	1,193	48%
	Apr-16	3/25/16	4/22/16	29	55	3,156	1,887	1,269	67%
	May-16	4/23/16	5/23/16	31	59	2,325	1,559	766	49%
	Jun-16	5/24/16	6/23/16	31	68	1,455	775	679	88%
	Jul-16	6/24/16	7/22/16	29	75	788	259	529	205%
	Aug-16	7/23/16	8/24/16	33	77	1,230	244	985	403%
	Sep-16	-	-	-	-	-			
	Oct-16	9/24/16	10/24/16	31	58	1,926	1,586	340	21%
	Nov-16	10/25/16	11/22/16	29	50	2,398	2,288	110	5%
Total						28,910	21,942	6,968	32%

EUI analysis

Using the weather normalized energy consumption, EUI during the pre-retrofit period was also compared with EUI during the post-retrofit period. EUI was calculated by dividing the annual total energy use by the building gross area of 84,053 ft^2. Using both the electricity and the natural gas use and the building gross area, and applying the conversion factors for source energy (as recommended by the EPA), **the EUI during the pre-retrofit period and the EUI during the post-retrofit period were 145.0 $kBtu/ft^2$-yr and 167.1 $kBtu/ft^2$-yr, respectively, showing an increase of 15.2%.** Median EUI for office buildings is 148.0 $kBtu/ft^2$-yr

Conclusions and Further Analysis

The regression analyses carried out in this work developed six parameters that can be compared before and after retrofit; the balance-point temperatures (different for cooling and heating), the non-weather related energy use (different for electricity and natural gas), and the cooling and heating slopes. How do these regression parameters relate to building integrity and usage?

In general, the cooling and heating slopes are indicative of effective insulation of the building envelope. The steeper the slope, the less effective the building envelope is in insulating the building from the outside. In the Yanke building, windows make up a significant portion of the building envelope so the quality of the windows and the manner of installation and integration into the building envelope can have a significant impact on the slopes. We would expect any quality window retrofit to decrease the magnitude of both heating and cooling slopes, with the possible exception that a window with lower solar heat gain (something most new windows have) may increase heating loads because solar gain is beneficial during the heating season. Our analysis indicates that the magnitude of cooling slope increased dramatically while that of the heating slope slightly decreased. The increase in the cooling slope is the driving factor in the calculated increase in electricity use post-retrofit.

We would expect the weather-independent parameter to be insensitive to changes in the building envelope. It is, however, sensitive to changes in activity within the building. The most likely contributors to increase in weather-independent electricity use would be lighting and plug loads. Since there were no large unoccupied portions of the building in the pre-retrofit period, it is likely that the increase in electricity consumption that we observed is due to increased plug load. It is likely that there are more employees in the Yanke building during the post-retrofit period, most of whom operate computers, thus increasing the overall consumption. To put this in perspective, a typical Windows workstation with dual monitors may draw as much as 400 Watts. More modest systems would be half of that. The increase we observed in weather-independent usage was about 6,400 Watts, which is consistent with approximately 20-25 additional workstations in use.

The balance-point temperature is a little more complicated and can be impacted by several influences, the primary ones being the internal set-point temperature, the building envelope, and the internal loads of the building. Building internal loads refer to those things that generate heat other than the building HVAC system. Building internal loads are dominated by the number of people in the building, the building lighting, and the building plug loads, all of which serve to add heat to the building space.

In general, a building balance-point temperature for cooling season increases as the system set-point increases and decreases with additional internal loads. Improving the integrity of the building envelope will also tend to decrease the cooling balance-point temperature. Our analysis indicated an increase of cooling balance-point temperature which indicates a) an increase in set-point (making the building warmer during the cooling season), b) a decrease in building internal loads, or c) a decrease in the effectiveness in the building envelope.

In heating season, an increase in set-point, a decrease in building envelope effectiveness, or a decrease in building internal loads will tend to increase the heating balance-point temperature. However, an increase in internal loads could be offset by a decrease in building envelope effectiveness, essentially cancelling the two effects out. Given that we observed no change in the heating balance-point temperature and assuming the set-point didn't change, it is possible that the increase in internal loads (as observed in the electricity analysis) might have been cancelled out by a poorer performing building envelope.

Of all the results we found, the dramatic increase in weather-independent natural gas use is the hardest to explain. For most buildings, this component can be attributed to domestic hot water production, but the Yanke building uses electric hot water heaters.

One possible explanation, which is supported by the fact that the heating balance-point temperature is higher than the cooling balance-point temperature, the two systems (natural gas heating and electricity-driven cooling) experience considerable overlap. It's conceivable that the new windows contributed to this overlap because the building has a hot water perimeter radiator system designed to make up for heat loss at the windows.

Time of day analysis (further analysis)

It can be illustrative to look at the patterns of electricity use as a function of time-of-day. For this portion of the analysis, we binned all the hourly energy use by time of day, then found the 50th percentile, 90th percentile and maximum electricity use for that hour and plotted them as representative daily energy profile. To focus on the impact of the cooling system on energy use, we limited this analysis to those hours in which the OAT was higher than the cooling balance-point temperature, indicating that the air conditioning is likely running. Figure 8 shows the results of this analysis for the weekdays during the cooling period.

These plots consistently indicate a shift in energy use earlier in the day. One possible explanation is a change in building occupied hours, as entered into the building energy management system. The Yanke building, like most commercial buildings, has the ability to change internal set-points based on a schedule of building use. During the nighttime, the internal temperature is allowed to rise and ventilation is minimized. During the occupied hours, the system works harder to maintain lower temperatures and better ventilation. Due to the thermal mass of the building, the time of the morning at which the change is made is often 2-3 hours prior to the arrival of the building occupants. These plots suggest that the time to release the nighttime operating conditions was modified in or around the retrofit period, significantly increasing energy use in the 4-6 AM time frame.

However, one would not expect the post-retrofit energy use to be consistently higher throughout the day, as the 50^{th} and 90^{th} percentile data indicate.

Bottom line

Some of the observed and modeled increase in energy consumption can be attributed to increased activity within the Yanke building. In addition, it would appear that the building operating schedule has been changed, likely due to occupant complaints. However, these impacts are not large enough to explain the significant increase in energy consumption after the window renovation was completed and nearly all interpretation of the regressions leads to the conclusion that the building envelope post-retrofit is performing more poorly than it was before the retrofit.

The CEERI staff plans to continue this research by taking infra-red (heat sensitive) photographs of the outside of the building as the weather gets colder, thus making potential thermal bridge issues more obvious.

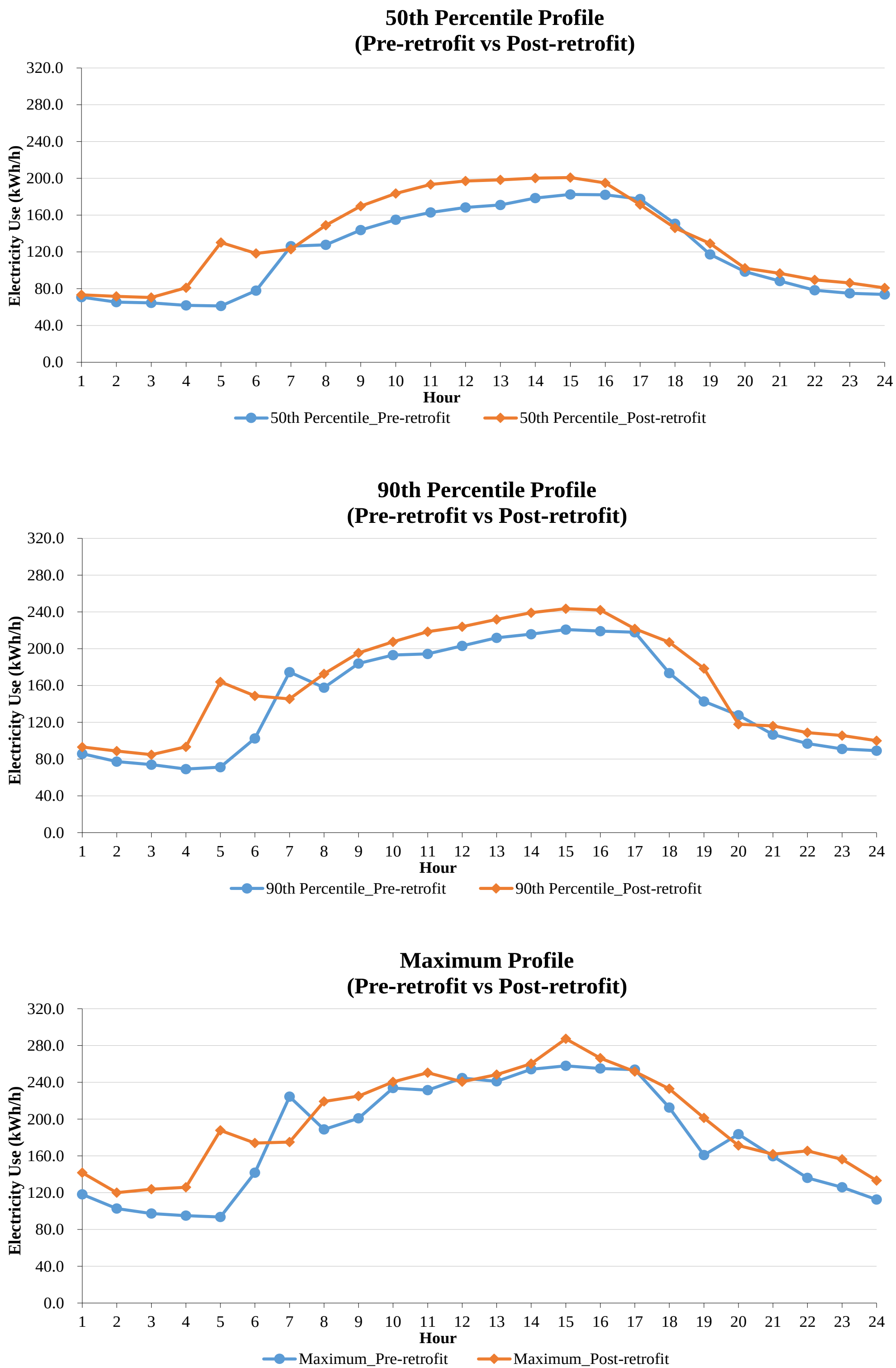


Figure 8. Comparisons of 50th percentile (upper), 90th percentile (middle), and maximum hourly electricity use (lower) ***when OATs are higher than the cooling balance-point temperature for the weekdays*** between the pre-retrofit period (July 2014 to April 2015) and the post-retrofit period (December 2015 to November 2016).

References

Energy Star. (2017). *What is energy use intensity (EUI)?* Retrieved from https://www.energystar.gov/buildings/facility-owners-and-managers/existing-buildings/use-portfolio-manager/understand-metrics/what-energy

Kissock, K., Haberl, J. S., and Claridge, D. E. (2001). *Inverse modeling toolkit: User's guide* (ASHRAE Final Report for RP-1050). Atlanta, GA: ASHRAE.

Kissock, K., Haberl, J. S., and Claridge, D. E. (2003). Inverse modeling toolkit: Numerical algorithms (RP-1050). *ASHRAE Transactions, 109,* 425-434.

Long, N. (2006). *Real-time weather data access guide* (Report Number NREL/BR-550-34303). Golden, CO: National Renewable Energy Laboratory.

National Oceanic and Atmospheric Administration (NOAA). (2017). *Data tools: Local Climatological Data (LCD).* Retrieved from http://www.ncdc.noaa.gov/qclcd/QCLCD?prior=N

Oh, S. (2017). *Quantifying the electricity savings from the Use of Home Automation Devices in a Residence. To be published in December.* (Doctoral Dissertation). College Station, TX: Texas A&M University.

Ott, R. L., and Longnecker, M. (2010). *An introduction to statistical methods and data analysis* (6th ed.). Belmont, CA: Brooks/Cole, Cengage Learning.

Sever, F., Kissock, K., Brown, D., and Mulqueen, S. (2011). Estimating industrial building energy savings using inverse simulation. *Proceedings of the ASHRAE Winter Conference, Las Vegas, NV*.