Performance Comparison of a Low-e Retrofit Window in a Philadelphia Office Building

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Figure 1. Office Building Upgraded with Low-e Window Retrofit Panels

Controlling rising energy costs in older multistory office buildings can take various pathways such as envelope or equipment improvements. Equipment upgrades, such as the use of high efficiency motors or boilers can result in reduced energy costs. However, for older building envelopes with lower wall insulation levels and lower performance windows with high U-factors, the efficiency gains from equipment improvements may be hindered. While the equipment may be more efficient, the discomfort of the occupants in inefficient buildings often leads to increased energy use (e.g., supplemental heaters are used in office spaces near windows). Furthermore, the equipment upgrades in older buildings must be sized to service the same loads whereas in more efficient envelopes, the equipment upgrades can be sized smaller thus saving upfront costs as well as ongoing fuel costs.

Envelope upgrades, however, can be very expensive for building owners. Envelope upgrade costs may include not only the installation of new materials, but also include removal and disposal of old materials, displacement of occupants during renovations, and modification of office sizes and floor space.

Addressing these concerns for envelope upgrades, an innovative retrofit window technology has been installed to decrease the window U-factor and add a low emissivity (low-e) coating. The window retrofit was performed on a 12-story office building located in downtown Philadelphia, Pennsylvania at 400 Market Street. The building was constructed in 1971 with single-pane windows. Prior to this retrofit, the only window alteration which had been performed was the addition of a window film on the interior surface. The window retrofits are performed such that occupants are not required to vacate office space and no existing materials other than the existing window film requires disposal.

The purpose for the window upgrade was to reduce operating energy costs; increase the comfort of the occupants, especially those located near windows; and provide a more uniform interior temperature that does not rely on use of supplemental heating units (in this case, baseboard heaters). The window upgrade technology selected is a unique retrofit panel product that effectively converts the original single-pane window into a triple pane low-e window system. Installed from the interior of the building, the low-e Retrofit Panel is a double pane, low-e coated glass panel installed on the interior of the existing window separated with a ½" gasket and held into place with an aluminum extruded frame.

The Low-e Retrofit Panel manufactured by JE Berkowitz, LP used for the window upgrades was the Renovate Platinum product. The retrofit panel is configured as a double pane IGU with one pane solar control low-e glass and one pane clear glass, filled with argon gas between the panes of the IGU. The center-of-glass U-factor of the final installed assembly (including the existing glass) is 0.18 and the solar heat gain coefficient is 0.44.

Test and Analysis Methodology

In order to understand the benefits of the low-e window retrofit panel upgrade and to compare the differences between the pre- and post-retrofit characteristics of the office space, two pairs of offices were instrumented with temperature sensors and controls, and an energy monitoring system connected to the specially installed heating and cooling systems for each office. All four of the offices were 10 ft. by 12 ft. with one nominal 6 ft. by 6 ft. window. One pair of offices was east facing and had an unobstructed view of the rising sun and one pair of offices had a northern exposure. For each pair of test offices, one office was kept with the original single-pane window with an interior film and the other office was retrofitted with the low-e retrofit panel. Prior to the installation of the low-e retrofit panel, the existing window film was removed to provide a clean surface on the existing window.

Figure 2. Side x Side Test Offices

Figure 3. Window Area in Test Office

The office pairs provide a side-by-side comparison of the room energy use, temperature, and light characteristics through both the heating and cooling seasons. Using dedicated heating and cooling equipment and performing infiltration testing, each office pair test was designed to isolate the influence of the window as the primary driver of heating and cooling energy use in the office space. In addition to isolating the heating and cooling energy (the building mechanical systems were deactivated in all four test offices), the test offices were outfitted with incandescent lamps to simulate internal gains from occupants and equipment. These simulated internal gains were controlled on a daily basis using programmable timers in accordance with weekday and weekend schedules consistent with the benchmark office building model from Pacific Northwest National Laboratory. Constant operating fans were employed to provide air mixing since the building ventilation system was closed off to the offices for the duration of the tests. Finally, the doors to offices were closed to isolate the offices from the adjoining common areas. The doors were outfitted with sensors to verify when and for what time length the doors were opened.

A programmable data logging system was used to control the temperature for the test offices which were kept at 69°F for heating and 71°F for cooling, through operation of the dedicated heating and cooling systems. The test offices and the common areas outside of the test offices are unoccupied during the monitoring period.

The test office energy use is used to analyze the pre- to the post low-e window retrofit panels. Though individual offices are a subset of the whole office building that includes conference rooms and open interior work space, the results do provide a controlled evaluation of the office spaces adjacent to windows. The results are representative of the savings expected for the perimeter areas of the building. Less clear in this analysis; however, is the effect that the windows will have on the core building heating and cooling energy (i.e., the office spaces without windows but separated by interior walls).

To better approximate the whole building performance, an initial analysis of the utility bills for the preceding year and the year following the window retrofit affords an opportunity to estimated actual savings. This analysis; however, is limited by changing building occupancy and weather patterns from year to year and thus serves only as a marker of energy savings. The benefit of the utility bill analysis is to generally confirm the savings based on the test office study and to generally estimate a magnitude of the savings that can be realistically expected from the window retrofits.

Lastly, the analysis provides general office light characteristics using photometric measurements to compare the pre- to post-window retrofit. A comparison of light levels and glazing temperatures are used to provide relative levels of lighting at different times of the day in various orientations and relative glazing temperatures, extremes of which can lead to discomfort for office personnel.

Instrumentation and Monitoring

Pairs of offices facing east (on the 6th floor) and offices facing north (on the 11th floor) were selected for the study. One of the test offices in the pair were upgraded with the low-e window retrofit panel and the adjacent office in the pair was left unaltered from the original single-pane glazing with interior solar control film. The building heating and cooling systems were shut-off and the ceiling diffuser for the ventilation system was sealed. The offices were tested for infiltration leakage and determined to be very similar in air leakage for each pair. Table 1 provides the leakage results at 50 Pa air pressure difference with the common area based on leakage measured from 10 Pa to 60 Pa in 10 Pa increments. The air leakage results indicate that leakage to the outdoors attributed to the glazing is negligible compared with the leakage to the adjacent common office space, and that the effects related to any air exchange to the interior should be equal within each pair.

Figure 4. Typical Instrumentation in Each Test Office

Figure 5. Cooling Unit, Mixing Fan, and Variable Light Loads

Table 1. Test Office Infiltration Test Results

50 Pa Pressure Difference	East Facing, Retrofit Panel	East Facing, Original Glazing	North Facing, Retrofit Panel	North Facing, Original Glazing
Leakage Flow, CFM	1,010	1,000	860	861

Each test office was equipped with two portable heaters – Broan model 6201-A (1500W) with blower fans for heating. A portable Sunpentown air conditioner model WA-1140DE (11,000 Btu/h) was installed to provide cooling. The condenser air flow was ducted to the common area outside of the test office. A separate floor fan was used to mix the room air to avoid stratification. The incandescent lamps, used to simulate internal gains from office personnel and equipment, were controlled by a programmable timer.

Interior temperatures were measured at three levels. The mid-level temperature was measured using a Vaisala humitter that records temperature and humidity and was used as the source temperature for space conditioning control. Other room temperatures were measured using Type T thermocouples. Type T thermocouples were also used to record temperatures on the interior glass surface. One other temperature sensor was placed on the exterior of the test offices in the common area. This temperature reading was used to modify the test office set temperature based on the setback or setup of the HVAC system during nighttime or weekend periods.

Light levels were recorded using a LiCor-210 Photometric sensor used to measure interior lighting levels primarily from the window. Differences in light levels based on the glazing coatings and films were intended to provide a qualitative, rather than quantitative, comparison between the adjacent test offices. The photometers were located in a horizontal position within three feet of the window center (see Figure 4 for representative location).

A Campbell Scientific data logger was used to both program the space conditioning control and record energy, temperature, and light data. The data was measured in five-second increments and averaged over a 15-minute period.

Monitoring was conducted from November 2011 through October 2012.

Perimeter Office Monitoring Results

The data presented in subsections below is based on each office, one pair facing east and one facing north. One office in each pair has been upgraded with the low-e window retrofit panel while the adjacent office has been unaltered from the original single-pane glazing with an interior solar control film.

Test Office Energy Use Comparison

The primairy metric to quantify the benfit of the retrofit window panels is energy consumption. The office test study is designed to isolate the effect of the window upgrades as the sole driver for energy conmsumption diffeences between offices in each pair.

Space conditioning energy was calculated for a heating period from December 1, 2011 through February 29, 2012 and a cooling period from July 27, 2012 through September 30, 2012. These periods were selected as primary heating and cooling periods where there was the least crossover between heating and cooling system operation. Table 2 provides a summary result of the energy consumption in heating and cooling for each test office.

Table 2. Estimated Energy Savings for Test Offices

Test Office/Orientation	Heating Energy[A], kWh	Cooling Energy[B], kWh
	December - February	July 27 - September[C]
East, Original Glazing, Film	372	341
East, Low-e Retrofit Panels	226	217
East Office Energy Savings	**39%**	**36%**
North, Original Glazing, Film	863	222
North, Low-e Retrofit Panels	343	202
North Office Energy Savings	**60%**	**9%**

[A] Heating Energy is adjusted to account for minor discrepancies in the Internal Gains in each office pair based on a 1:1 ratio.
[B] Cooling energy is adjusted to account for minor discrepancies in the Internal Gains in each office pair based on an EER of 9.0.
[C] Cooling data period constrained by errant operation of one AC unit.

The energy use data for space conditoning in offices with a direct connection to a window results in the following summary observations for an annual period:

- For offices with access to direct solar gains (i.e., unshaded east, west, south orientations), the low-e window retrofit panels result in about 40% heating energy savings over the existing windows. North facing offices result in about 60% heating energy savings with the low-e window retrofit panel.

- For offices with access to direct solar gains (i.e., unshaded east, west, south orientations), the low-e window retrofit panels result in about 35% cooling energy savings over the existing windows. However, for north facing offices with inherently lower solar gains, cooling energy savings is more modest, generally less than 10% with the low-e window retrofit panel.

Two general performance concepts highlighted by the window retrofit are demonstrated by these summary energy use results:

- Heating energy savings is greater for window orientations that do not have direct solar gain , because heat transfer in the space is dominated by thermal heat loss through the windows, so improvements in the U-factor of the window assembly have a larger impact. For other window orientations that do have direct solar gain, the solar heating offsets a portion of the energy needed for space heating, so the savings due to the improved window U-factor are significant but not as high as on the north side.

- Impact on cooling energy savings is more complicated since energy savings varies widely depending on the orientation of the windows. Cooling periods have a lower temperature difference driver (rendering the U-factor improvement slightly less effective) while solar and internal gains play a much more prominant role. Furthermore, in some climatic conditions such as swing seasons, heat loss through the original less efficient windows at night may decrease loads on the cooling system, as is the case in this test. (This energy savings, however, may be offset by discomfort from large temperature changes at the surface of the glazing during the daytime.) Overall, the addition of the solar control low-e retrofit panel did result in significant cooling energy savings in the east-facing office by reducing the solar heat gain, and the same would be expected for other orientations with direct solar gains.

In many commerical buildings, the electric peak demand may be a significant factor in energy costs. While the testing of this study can only point to potential demand savings, the opportunity to reduce demand charges can be demonstrated by comparing the demand for each office in both orientations. Figure 6 and Figure 7 show the electic demand curve for each set of offices in both orientations, based on measured electric data for each office. The heating for this test was from electric heaters so is not representative of the building energy supply for heating (which is natural gas).

The electric demand curves demonstrate the reduced demand for the offices with the low-e retrofit panels. General observations include:

- Heating peak demand in north facing rooms is double that of the east facing (and by extension west and south) offices.
- The demand for heating decreases and ends more rapidly with the window retrofit panel upgrades.
- Cooling demand in the east facing (and by extension, the west and south) offices is significantly lower and decreases much more rapidly with the window retrofit panel upgrades. Cooling peak demand is reduced by over 10% and remains over 10% for nearly a quarter of the cooling period.
- Cooling demand in north facing offices demonstrates modest, but measurable benefit from the retrofit panel upgrades.

Test Office Interior Temperature Comparison

A secondary metric of interest to compare the perfomance of the low-e window retrofit panels with the existing single-pane glazing with solar control film is the temperature changes in the room and on the glazing surface. The following four figures (Figure 8 through Figure 11) provide an example of the temperature profile for a cold sunny winter day and a hot sunny summer day, for each test office orientation.

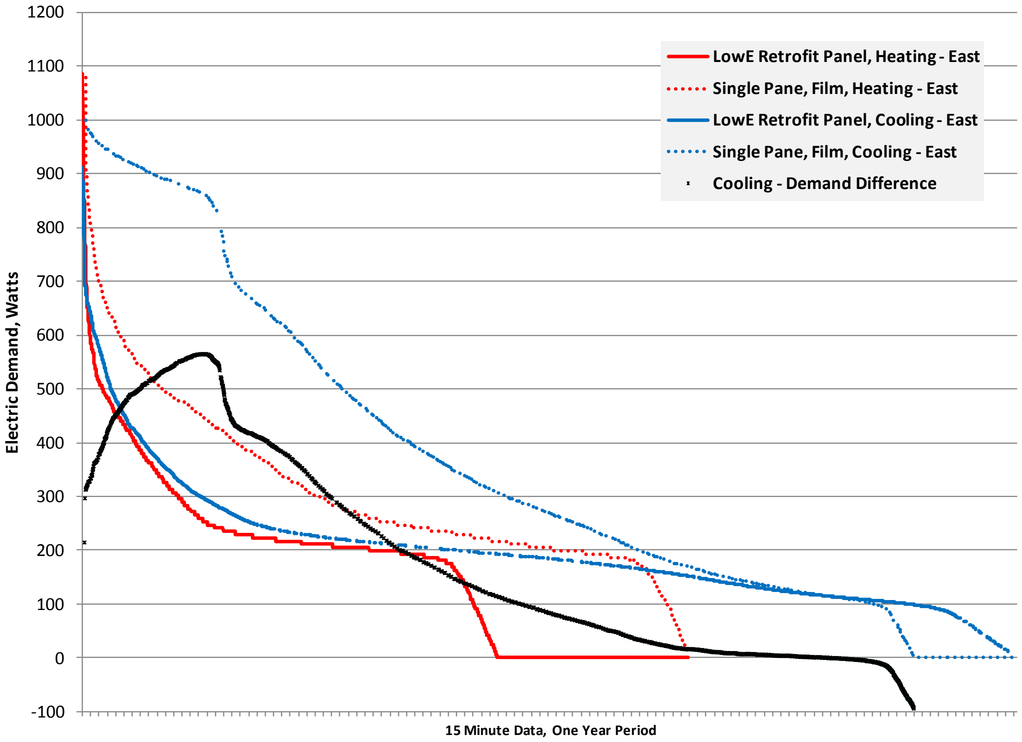


Figure 6. Electric Demand - East Facing Offices

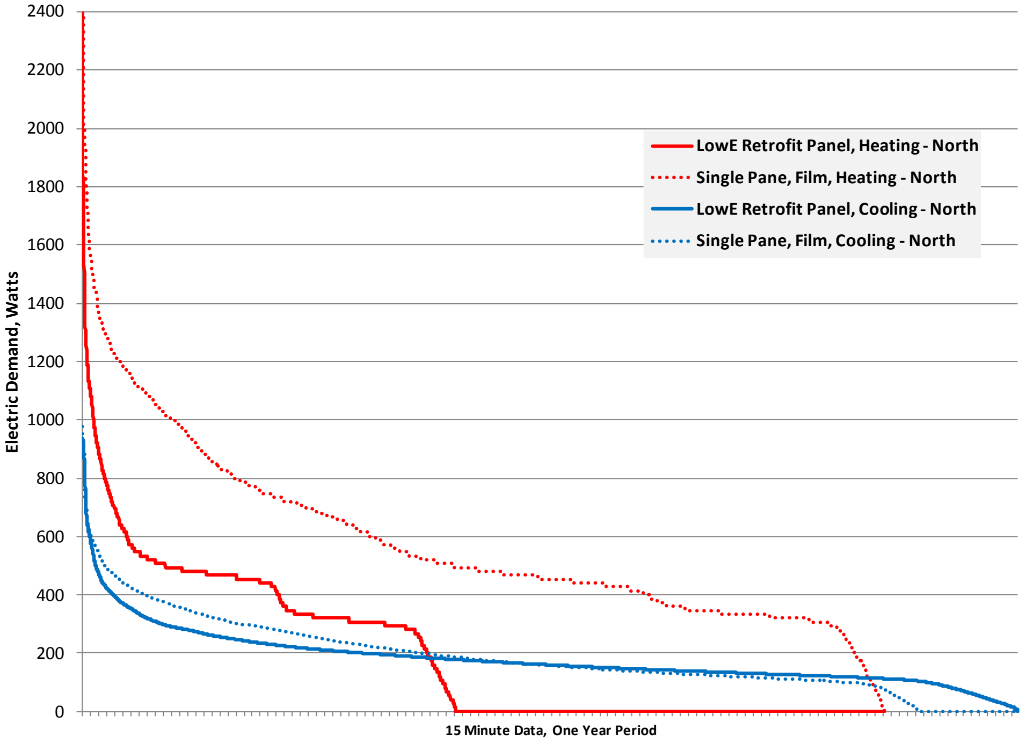


Figure 7. Electric Demand - North Facing Offices

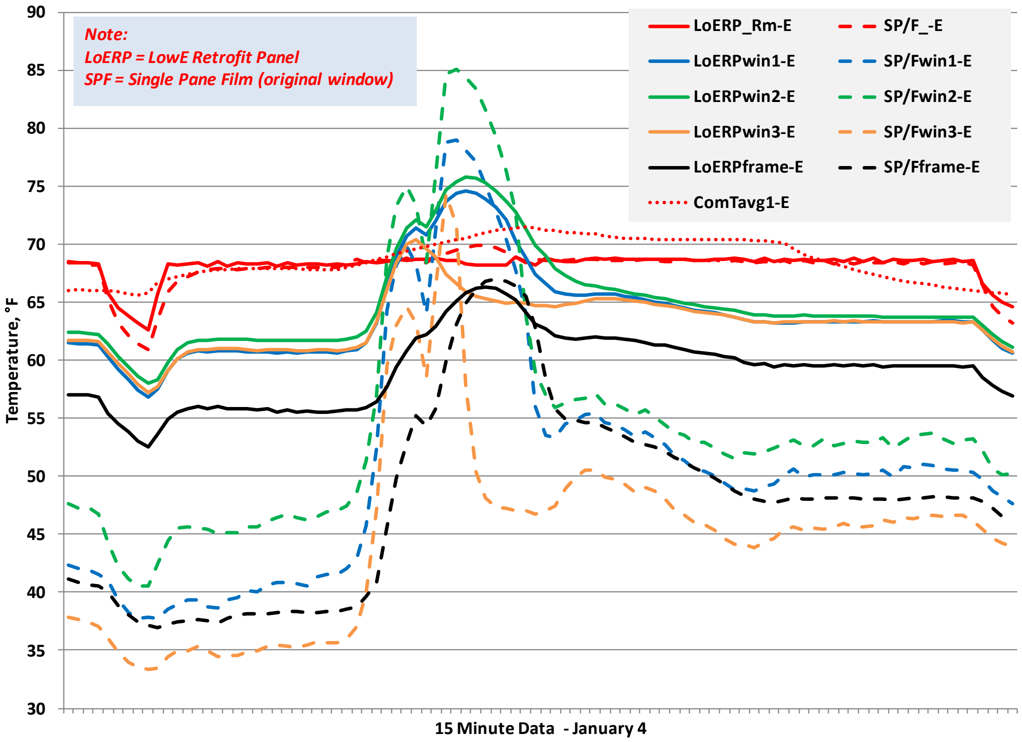


Figure 8. Glazing Surface Temperatures - East-Facing Test Offices, Winter Day

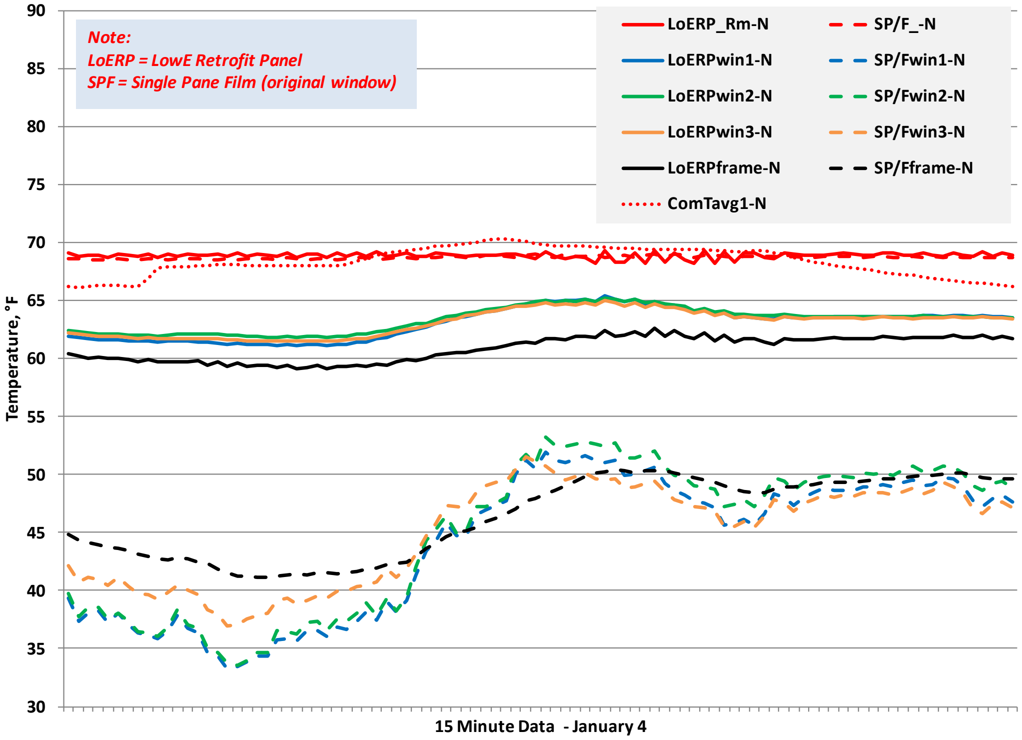


Figure 9. Glazing Surface Temperatures - North-Facing Test Offices, Winter Day

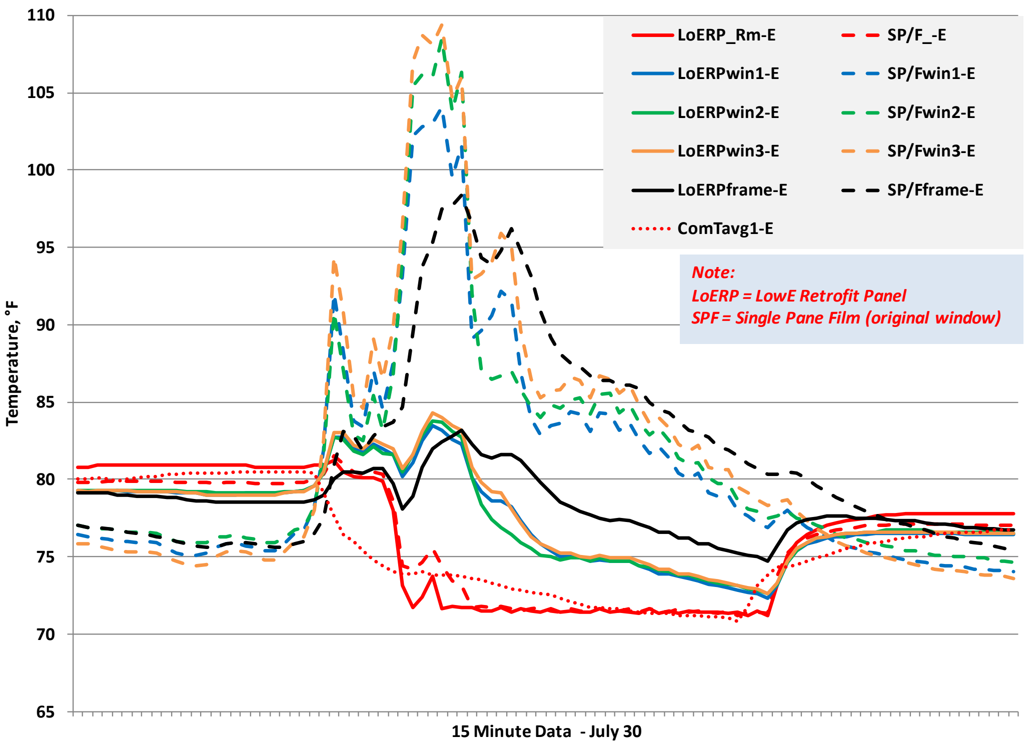


Figure 10. Glazing Surface Temperatures - East-Facing Test Offices, Summer Day

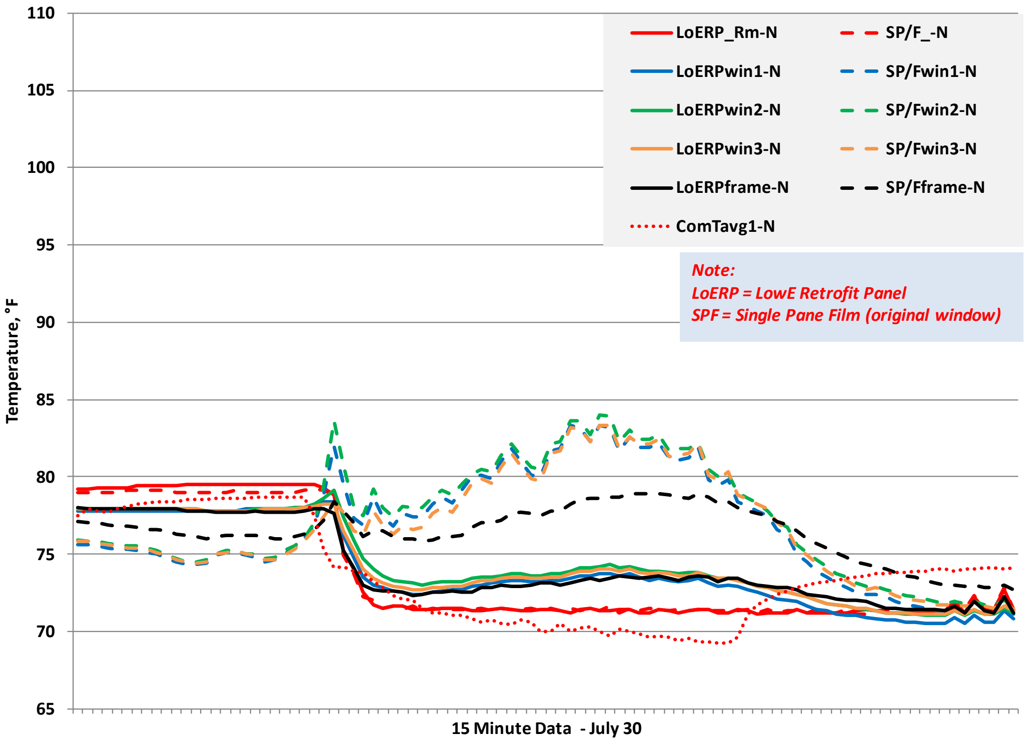


Figure 11. Glazing Surface Temperatures - North-Facing Test Offices, Summer Day

The differences between the window surface temperatures is clearly identified with the orignal single-pane glazing temperatures on the interior surface of the windows at approximately 15°F higher or lower than similar peaks on the interior window surface of the low-e retrofit panels. More pronounced; however, is the temperature swing in a single diurnal period as summarized in Table 3.

Table 3. Diurnal Glazing Surface Temperature Range for Selected Periods

Inside Glass Surface Temperature Profile	East Facing		North Facing	
	Low-e Retrofit Panel	Original Single Pane/Film	Low-e Retrofit Panel	Original Single Pane/Film
Winter day, Maximum during day	70 - 76°F	75 - 85°F	65°F	52 - 53°F
Winter day, Minimum during day	57 - 58°F	33 - 40°F	61 - 62°F	34 - 37°F
Summer day, Maximum during day	84°F	104 - 109°F	73 - 74°F	83 - 84°F
Summer day, Minimum during day	72 - 73°F	74 - 75°F	71°F	72°F

For the East facing windows, the inside surface temperature of the glass for the low-e retrofit panel may vary by almost 20°F depending the location on the glass, the outside temperature, and the level of solar radiaition. For the existing glazing with the solar control film, the range may be over 50°F in a diurnal period. For the north facing windows, the range for the low-e retrofit panel is only a few degrees (since no direct solar impinges on the surface), and ranges to 19°F for the original single pane with solar control film. The significantly reduced temperature swings for the windows with the low-e retrofit panel would be expected to improve occupant comfort and reduce the use of supplemental heating/cooling systems.

Light levels were measured in each test office using photometers located within three feet of the window. Light levels were generally driven by light through the window areas, rather than electrical lighting. Figure 12 shows the relationship of the light level for each pair of offices as a percentage of the maximum measured across all office pairs (i.e., the east-facing LowERP office which has the highest light levels across all four test offices). The light levels are sorted on the largest values. As expected, the east facing rooms (red curve, left axis) have a sharp decline in light levels once the sun moves toward the southernly sky. The north-facing offices (blue curve, right axis) have a much smaller maximum, about one-tenth that of the east facing rooms but have a more modest slope. For the north-facing offices, it is apparent that the low-e retrofit panel provides more light than the darker solar control film on the original window.

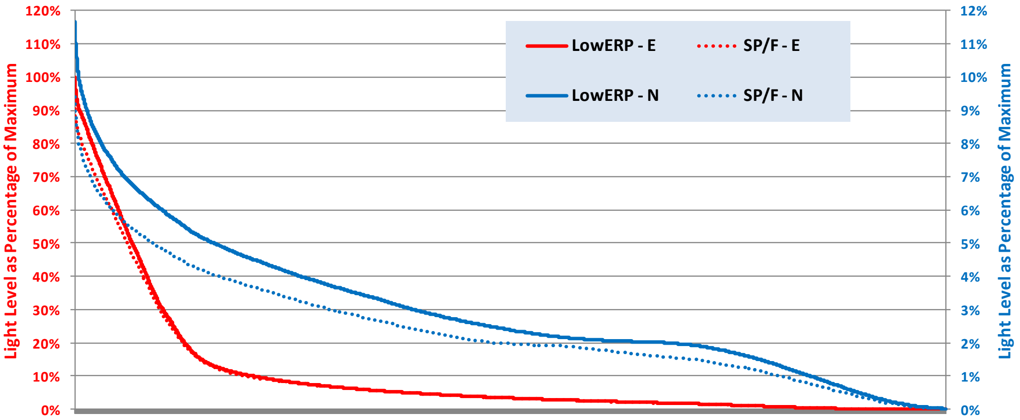


Figure 12. Relative Light Levels Measured in Each Office Space over Monitoring Period

Whole Building Energy Use Estimates

Following the retrofit of the entire building with low-e window retrofit panels, an initial analysis of utility bills was performed. The utlilities include gas use and electric use. Both heating and cooling periods prior to the window upgrades was compared with heating and cooling periods following the window upgrades. The utility bill analysis is complicated by different weather conditons, variable building occupancy, and any changes in office space by individual tenants. However, a general analysis is reasonable as an indication of expected savings given that future higher occupancy levels will likely confirm or enhance energy savings.

Natural gas and electric utility bills from portions of 2010 through 2013 were obtained and arranged into seasonal periods for before- and after-window upgrades. Using weather data, a calculation of heating and cooling degree days was made for the same periods. Degree days are used to normalize utility data across seasonal periods. Figure 13 shows the rollup of the data used for comparison of the pre- and post-window retrofit (non-normalized results). Given the much colder period in the 2010-2011 heating season, fuel use is expected to be higher.

Based on a select portion of the heating season (periods when there is little crossover cooling expected) the energy use is normalized to the heating degree days for the respective periods. Figure 14 shows the normalized use and calculated savings in post-window retrofit in the 2nd and 3rd heating seasons. The savings is 28% (season 2) and 23% (season 3) over the base first year. Given the mild winter in the 2011-2012 heating season and the changes in occupancy, the estimated savings attributed to the window upgrades is generally about 25%.

Figure 15 depicts the primary cooling season whole building electrical usage and cooling degree days over a monthly period. Whole building electric includes all electric loads; however, increases in electricity use over periods of mild outdoor temperatures would approximate the cooling energy use apart from other electricity uses.

Given that the electricity use for cooling is only a portion of the totals building electricity, a rough estimate of cooling energy is made by subtracting from the peak cooling months, the electricity use in a month that has minimal cooling (and heating), in this case the April monthly use. Figure 16 shows the estimated cooling electricity use for two cooling periods prior to the window upgrades, and one cooling period following the window upgrades. The cooling energy is not normalized to cooling degree days since the relationship is tenuous at best given the large influence of internal gains and limited data set to monthly resolution.

In addition to the total electricity use, the peak power demand is also an important factor in utility costs. Electricity demand, as reported on utility billing, for pre- and post-window retrofit periods is shown in Figure 17.

With only the limited data set, it appears that the peak electricity demand has remained somewhat consistent from pre- to post-retrofit periods, indicating that peak demand is driven by numerous factors in addition to window loads.

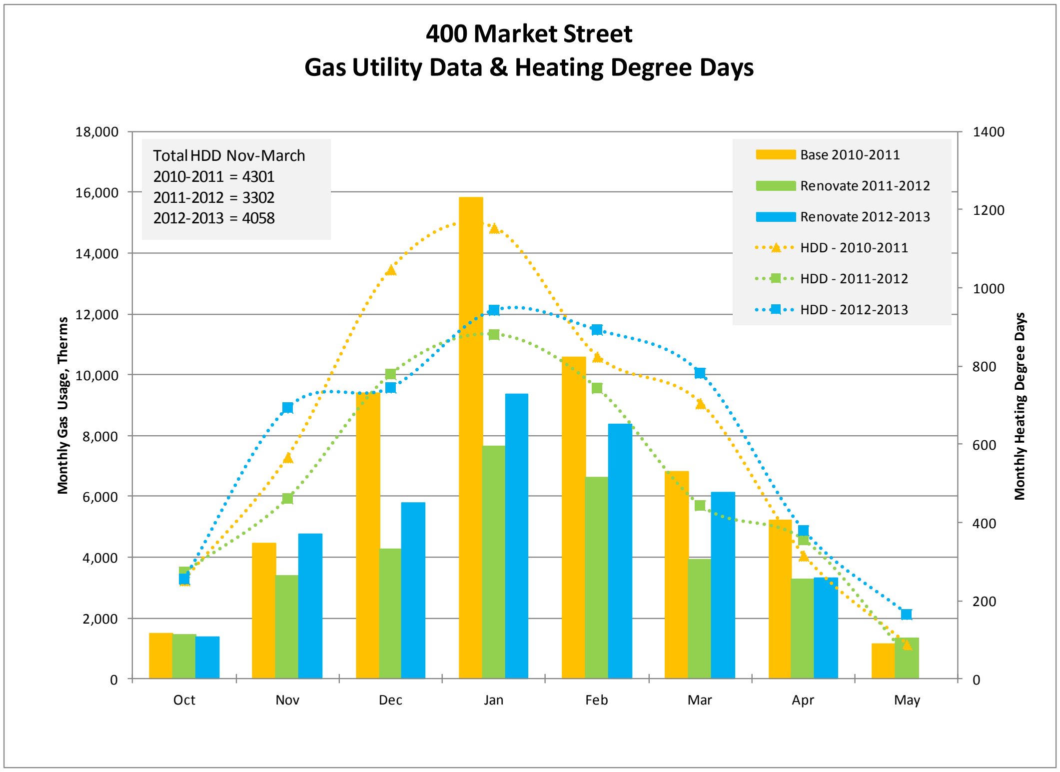


Figure 13. Monthly Fuel Use for Pre- and Post-Window Retrofit

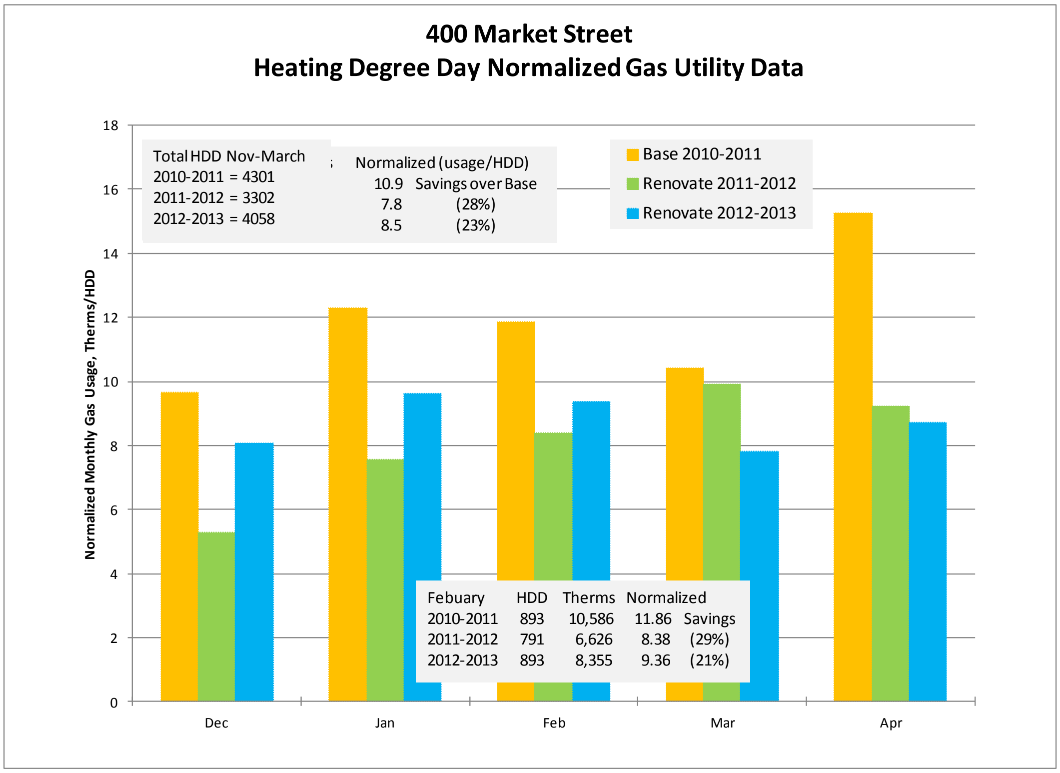


Figure 14. Normalized Heating Fuel Use

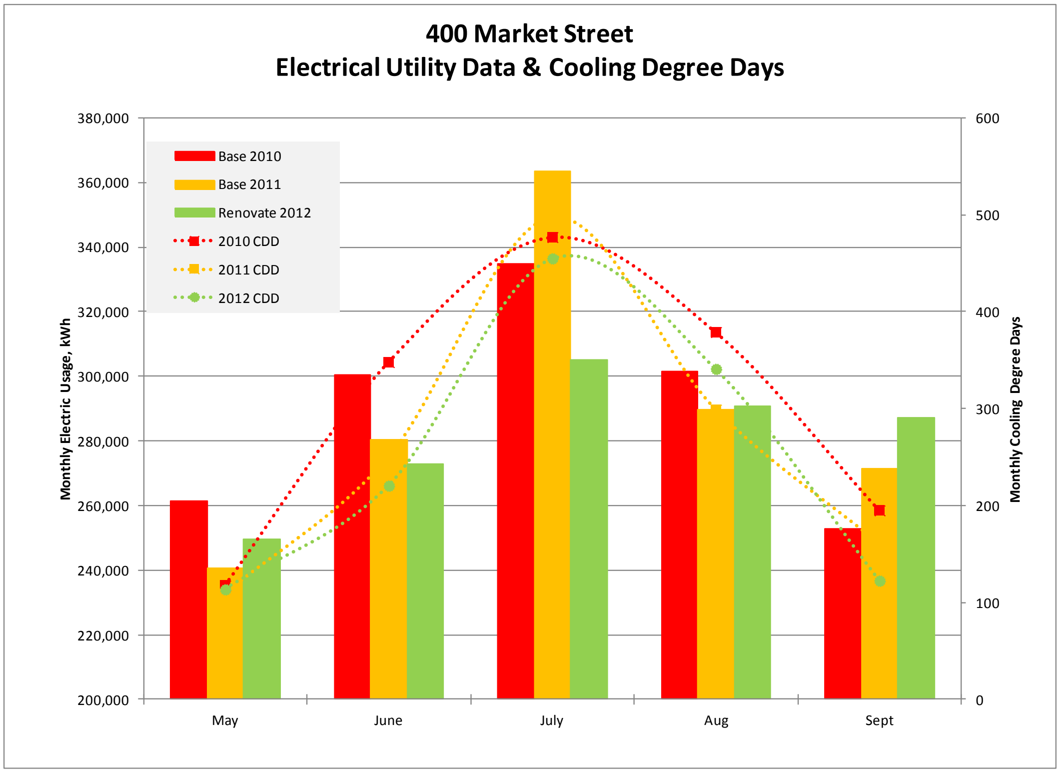


Figure 15. Monthly Electricity Use for Pre- and Post-Window Retrofit

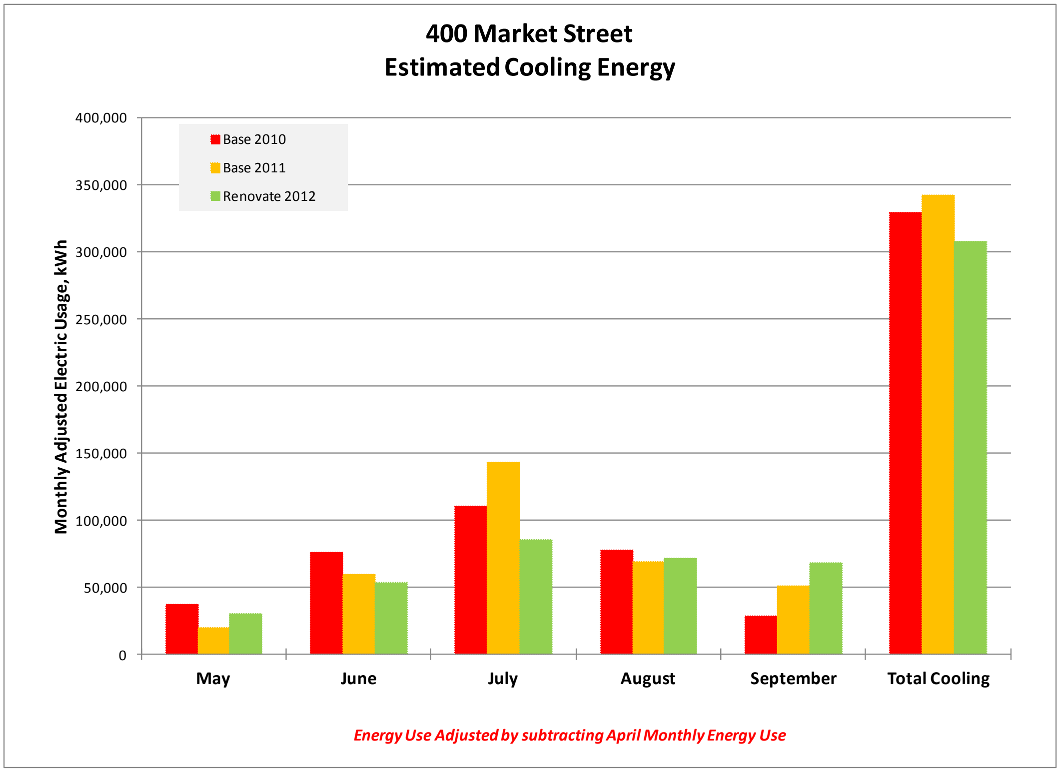
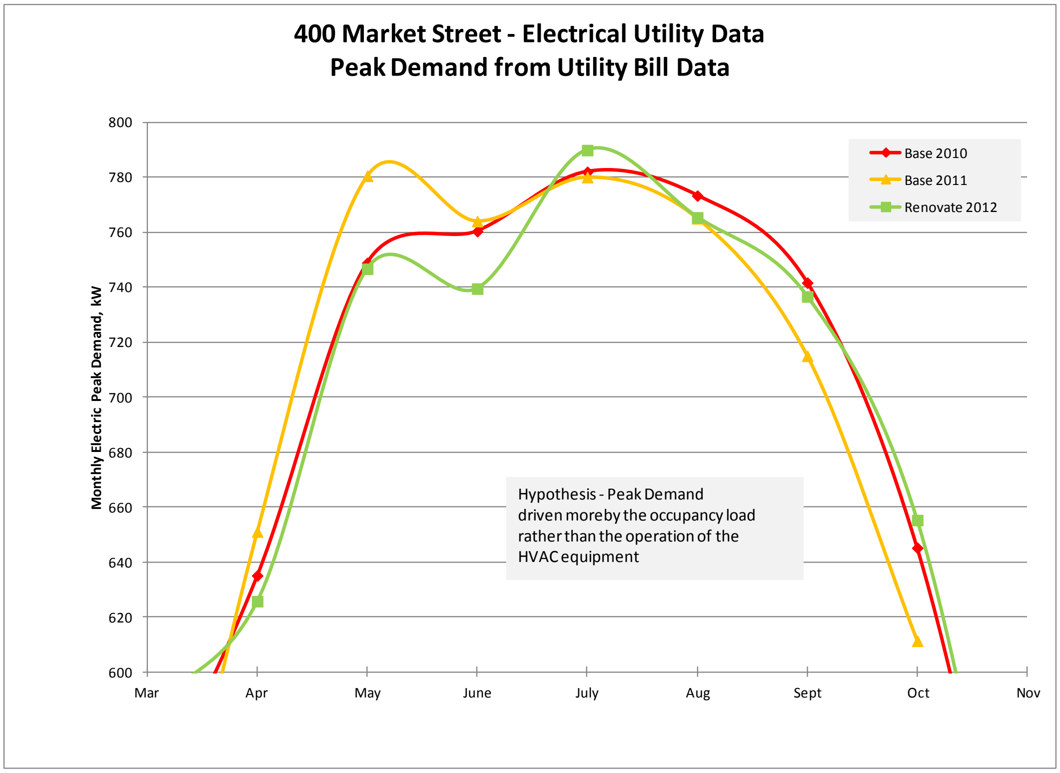


Figure 16. Estimated Cooling Electricity Use


400 Market Street - Electrical Utility Data
Peak Demand from Utility Bill Data

Hypothesis - Peak Demand driven moreby the occupancy load rather than the operation of the HVAC equipment

Figure 17. Monthly Peak Power Demand for Cooling Periods

Energy usage based on utility bill data does demonstrate energy savings when comparing pre- and post-retrofit periods for heating but is much less clear for cooling energy savings. Heating energy savings may be identified more clearly in the relationship with outdoor temperatures as the temperature difference between interior and exterior is much larger than in warmer seasons. Due to the lower indoor-outdoor temperature difference in cooling and the more variable latent load removal, the direct relationship between temperature conditions in cooling is not representative for this climate. Table 4 shows the overall energy use and estimated savings based solely on utility bill data.

Table 4. Energy Use Comparison Based on Monthly Utility Billing

Heating	11/2010 to 03/2011[A]	11/2011 to 03/2012[B]	11/2012 to 03/2013[B]
Heating Degree-Days, HDD	4301	3302	4058
Gas Use, therms	47080	25895	34358
Normalized Use, therms/HDD	10.9	7.8	8.5
Heating Savings Over Base		28%	23%
Estimated Electric for Heating, kWh	139,923	42,333	116,057
Normalized Use, kWh/HDD	33	13	29
Electric Savings Over Base		61%	12%
Combined Gas/Electric Heating Savings Over Base[C]		31%	22%

Cooling	05/2011 to 09/2011A	05/2012 to 09/2012A	05/2013 to 09/2013B
Net Cooling Electricity Use, kWh	328,944	341,784	307,583

[A] Pre-window retrofit.
[B] Post-window retrofit.
[C] Calculated using a site conversion to Btu and normalizing with HDD

Conclusions

The energy efficiency upgrade of low-e window retrofit panels at the 400 Market St. office tower has demonstrated significant energy savings when evaluating office spaces directly influenced by the window upgrades. Heating energy reductions of between 40% and 60% were measured in perimeter offices, with the largest benefit occurring in offices with less direct solar gains (such as the north orientation). Cooling energy savings ranged from less than 10% to over 35%, with higher energy savings in the offices more influenced by solar gains.

Window interior surface temperatures were found to be far less variable following the installation of the retrofit panels, with diurnal variations only about 4°F for the retrofit panel and nearly 20°F for the original window in the north orientation. When exposed to direct solar gain in the summer, the maximum interior glass temperature was reduced by more than 20°F for the retrofit panel office. The reduced daily temperature swing and extremes are expected to result in a higher level of comfort for personnel working near window areas. This benefit is anticipated for all window orientations.

In addition to energy savings and comfort enhancement, room light levels were found to be very similar or slightly higher for the low-e retrofit panel offices than the original single-pane clear glazing with solar control film.

Peak electricity demand, based on utility bill reporting, appears to remain the same for the whole building for pre- and post-retrofit periods, although significant reductions in cooling demand was observed in the east-facing perimeter office.

An initial utility bill analysis, which includes all building office space, indicates that gas savings resulted in about 25% gas use reduction and generally the same for the electricity used for heating. Cooling energy savings from utility bills is much less clear given the effects of occupancy and weather variables of direct solar gains, and latent loads. Analysis of ongoing utility costs and a review of the heating and cooling equipment operation with building engineers is recommended to fully understand the benefits of the window upgrades.

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