University of Dayton Kettering Labs
Window Energy Use Analysis

By

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Executive Summary

On January 9, 2007, Joe Saliba, Dean of the School of Engineering, requested an analysis to determine the energy cost savings from replacing the current double-pane aluminum-frame casement windows in Kettering Labs with Pella double-pane wood-frame double-hung windows. The proposed windows with and without a low-emissivity coating were analyzed. This report summarizes the results of this analysis.

The methodology used involved the following steps:

I. Characterize properties of current and proposed windows.
II. Characterize current "baseline" energy use based on measured data.
III. Simulate baseline energy use and calibrate simulation model to baseline data.
IV. Simulate energy use with proposed windows.
V. Calculate expected savings as the difference between the simulated baseline and expected energy use. Calculate the present value of the energy cost savings over the lifetime of the windows.

Using this methodology, anticipated initial energy cost savings from replacing the current windows are about $4,600 per year for Pella double-glazed windows, and $5,500 per year for Pella low-e double-glazed windows.

Assuming the same real energy cost escalation rate as from 1995 to 2005, the present value of energy savings over the 30-year lifetime of the windows is about $143,000 for Pella double-glazed windows and $172,000 for Pella low-e double-glazed windows.

Anticipated CO_2 emission reductions from replacing the current windows are about 23 tonnes per year for Pella double-glazed windows, and 28 tonnes per year for Pella low-e double-glazed windows.

I. Current and Proposed Windows

The windows being considered for replacement are operable, double-glazed, casement-style windows with aluminum frames. The windows pivot about a vertical axis through the center of the window, and the edge of the window has a rubber gasket. The gross dimensions of the windows, including the aluminum framing surrounding the operable part of the window, are 44 in x 58 in for a gross area of 17.7 ft^2. The dimensions of the operable part of the window, including the aluminum frame and glazing are 57 in x 36 in. The dimensions of the glazing are 51 in x 36 in for an area of 10.8 ft^2. The number of windows and gross window area on each exposure of Kettering Labs (KL) are shown in Table 1.

Exposure	Gross Operable Window Area
North	88 win x 17.7 ft^2/win = 1,558 ft^2
South	82 win x 17.7 ft^2/win = 1,451 ft^2
East	56 win x 17.7 ft^2/win = 991 ft^2
West	80 win x 17.7 ft^2/win = 1,416 ft^2
Total	306 win x 17.7 ft^2/win = 5,416 ft^2

Table 1. Gross operable window area.

The thermal performance of a window is characterized by three variables: the conductance, solar heat gain coefficient and air tightness. The overall conductance, U, of a window includes the conductance of the frame and glazing. The overall conductance of aluminum frame windows is higher than wood frame windows, because of high conductance of the aluminum frame. Conductance through glazing can be reduced by adding layers of glazing, filling the space between glazings with argon, and applying low e coatings the glazing to reduce radiation exchange. The solar heat gain coefficient, SHGC, is the fraction of solar energy incident on the window which is transmitted into the space. The overall SHCG of the window includes solar radiation incident on the frame and glazing. Air leakage, V, is characterized by the rate of air leakage at a nominal pressure difference across the window. All three of these variables vary with the size of the window, since the ratio of frame to glazing varies with window size. However, manufacturers generally report data only for a typically-sized window. Thus, the nominal values of U, SHGC and V for typically-sized windows will be used in this report.

This analysis compares the performance of the current double-glazed, aluminum frame, windows to Pella Designer Series double-glazed, clad wood frame, double-hung windows (Groesbeck, 2007). Windows with and without a low-emissivity coating on the hinged class panel (HGP) were considered. It is assumed that the new windows will be sized to replace the gross area of the current windows and eliminate all aluminum framing. Thermal performance metrics for each type of window are shown in Table 2. The data show that the current aluminum-frame windows conduct heat more readily, allow more solar heat into the building, and are leakier than the proposed Pella windows.

	U (Btu/hr-ft2-F)	SHGC	V (cfm per ft^2 frame area at 1.57 lbf/ft^2 wind pressure)
Double-glazed aluminum frame	0.76[1]	0.68[1]	0.47[3]
Pella Designer Series, 3mm, double-glazed, clad wood-frame, double-hung[2]	0.51	0.56	0.30
Pella Designer Series, 3mm, double-glazed, clad wood-frame, double-hung, low-e[2]	0.41	0.53	0.30

Table 2. Thermal performance of windows. 1: Efficient Windows Collaborative, 2007. 2: Pella, 2005 for window with gross dimensions 47 in x 59 in. 3: Value estimated using method shown below.

The current windows have louvers between the two panes of glass. It is suggested that the proposed windows also have louvers between the two panes of glass to control light levels. It is also suggested that the louvers in the new windows be concave up, instead of down, to direct natural light onto the ceiling and farther into the space. Closed louvers decrease the conductance and solar heat gain coefficient of the windows. According to tests by Pella, closed louvered blinds decrease the U-value by 0.05 Btu/ft^2-hr-F (Pella, 2007). However, due to the intermittent closing and opening of louvers, these effects were not considered in this analysis.

This report considers the savings from replacing the current windows with proposed double-hung windows. However, it is noted that casement windows may be more architecturally consistent with the current windows. In addition, because the casement windows can be locked against the window frame, Pella casement windows have air leakage rates of 0.05 cfm per ft^2 frame compared to 0.30 cfm per ft^2 frame for double-hung windows (Pella, 2005).

Air Leakage through Current Windows

The current casement-style windows pivot about a vertical axis through the center of the window. The edge of each window has a rubber gasket. However, the windows cannot be locked into a position that seals the gaskets against the frames; thus air leaks into and out of the building around the gaskets. No published data showing the air leakage rate through the current aluminum-frame windows was available. Thus, the air leakage through the current windows was estimated using the following method.

Newton's second law was applied to estimate the wind velocity that would cause a wind pressure of 1.57 lbf/ft^2. Assuming that the wind comes to a complete stop when impacting the window, the wind velocity, $\underline{V}$, at air density ρ, to produce a given pressure P, is given by Equation 1. From Equation 1, a wind velocity of about 18 mph is needed to produce a wind pressure of 1.57 lbf/ft^2.

$\underline{V} = (P / \rho)^{0.5}$ (1)

To estimate the leakage rate of the current windows at this condition, the speed of air leaking around the rubber gasket of a window in Kettering Lab on a breezy January afternoon with wind velocities near 20 mph was measured. The average air speed was about 40 ft/min, with air speeds through some gaps at over 200 ft/min. The length of the rubber gasket is about 15.5 ft. Assuming an average crack width of 1/16th inch, the air leakage around the window was about:

40 ft/min x 1/16/12 ft x 15.5 ft = 3.23 ft^3/min

The air leakage per square foot of frame area was about:

3.23 ft^3/min / 6.9 ft^2 = 0.47 cfm/ft^2 frame area

II. Baseline Electricity Use

Baseline electricity use data for Kettering Labs were supplied by the University of Dayton Energy Manager (Blevins, 2007). The data were analyzed using the Energy Explorer data analysis software (Kissock, 2004). The monthly electricity use of the building and the chiller from meter reading dates 9/15/2001 to 7/15/2006 is shown in Figure 1. Inspection of the building electricity use trend shows that electricity use varies from month to month, but the overall trend has remained fairly constant from 2001 to 2006. In addition, the chiller trend shows that the chillers are turned off during winter and that chiller electricity use peaks during summer months. Like building electricity use, the overall trend in chiller electricity use has remained fairly constant from 2001 to 2006.

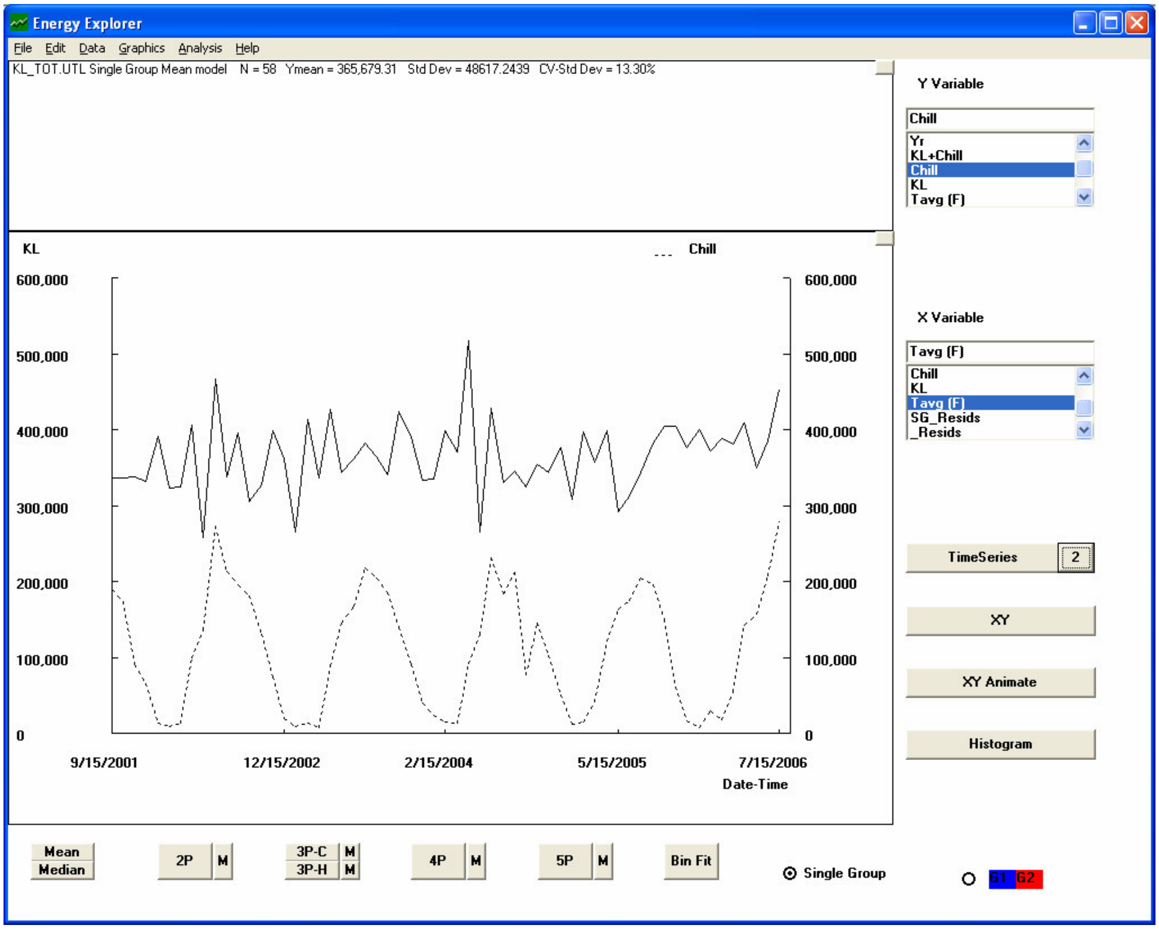

Figure 1. Monthly electricity use for the building and chiller at Kettering Labs from meter reading dates 9/15/2001 to 7/15/2006.

The month-to-month variation in building electricity use might be expected to follow the academic calendar; for example, electricity use might be expected to decline during the 1/15, 5/15 and 8/15 billing periods between semesters. However, close inspection of the data in Figure 1 show that the building electricity use does not consistently follow these expected patterns. Thus, there is no typical pattern of monthly electricity use. Because of the apparently random nature of monthly electricity use, the baseline monthly building electricity use is taken to be the mean monthly electricity use from 9/15/2006 to 7/15/2006. Mean electricity use by the building, KLB, is shown in Figure 2 and Equation 2.

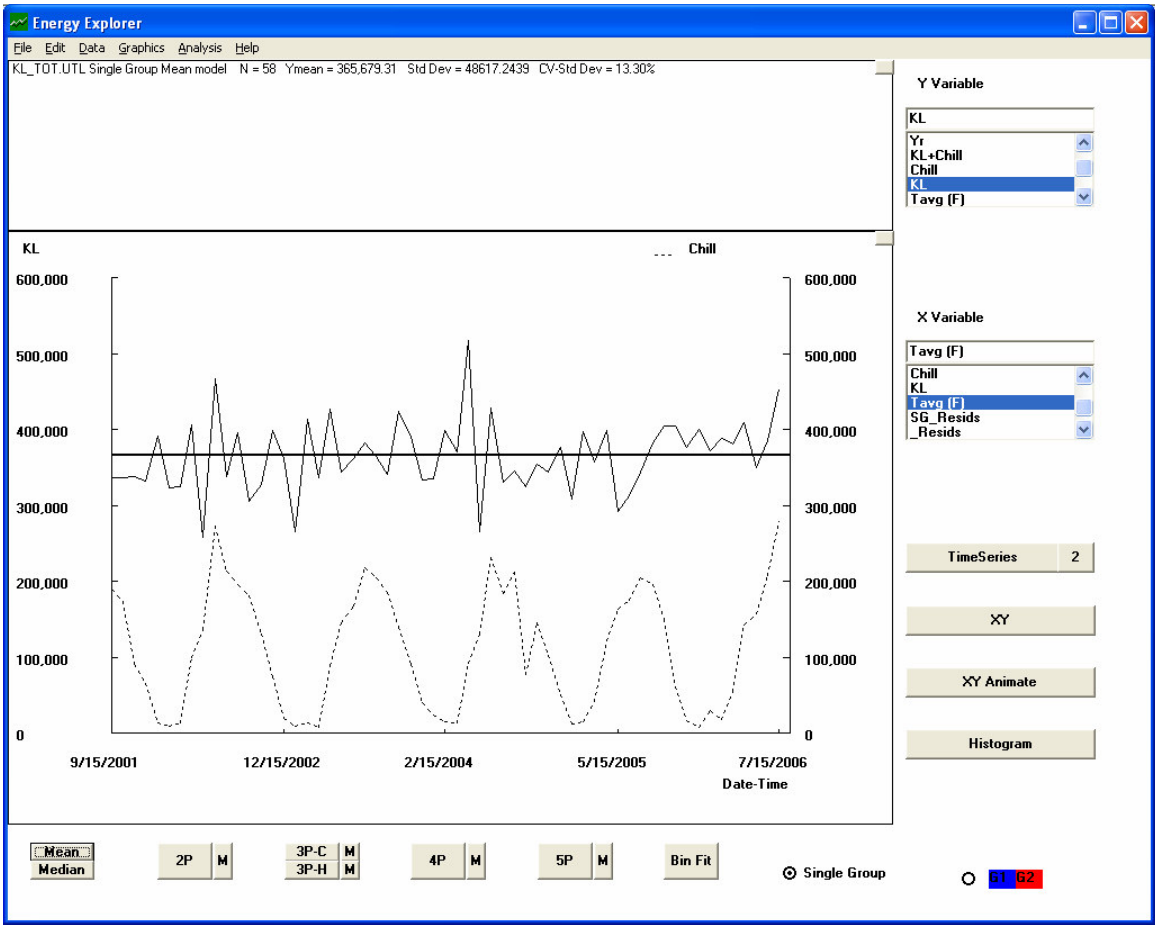

Figure 2. Mean monthly KL electricity use from 9/15/2006 to 7/15/2006.

KLB = 365,679 kWh/month = 12,022 kWh/day (2)

Average outdoor air temperatures for each day from 8/15/2006 to 7/15/2006 in Dayton, OH are available from the UD-EPA Average Daily Temperature Archive (http://www.engr.udayton.edu/weather/). Using these data, the average monthly air temperature for each electricity billing period can be computed. Monthly chiller electricity use is plotted against average monthly outdoor air temperature in Figure 3. The vast majority of data points are in group that appears to be linearly related to outdoor air temperature. However, five data points appear to be outliers from the general trend. It might be expected that the five circled outlying data points correspond to periods of unusually high or low whole building electricity use, which is an indicator of occupancy and would generate unusually high or low building cooling loads. However, close investigation indicates that the circled outlying data points do not appear to be caused by changes in building electricity use. Thus, in order to describe the most typical relationship between electricity use and outdoor air temperature, the 6/15/2002, 7/15/2006, 11/15/2005, 10/15/2005 and 9/15/2005 outlying data points were removed from the data set.

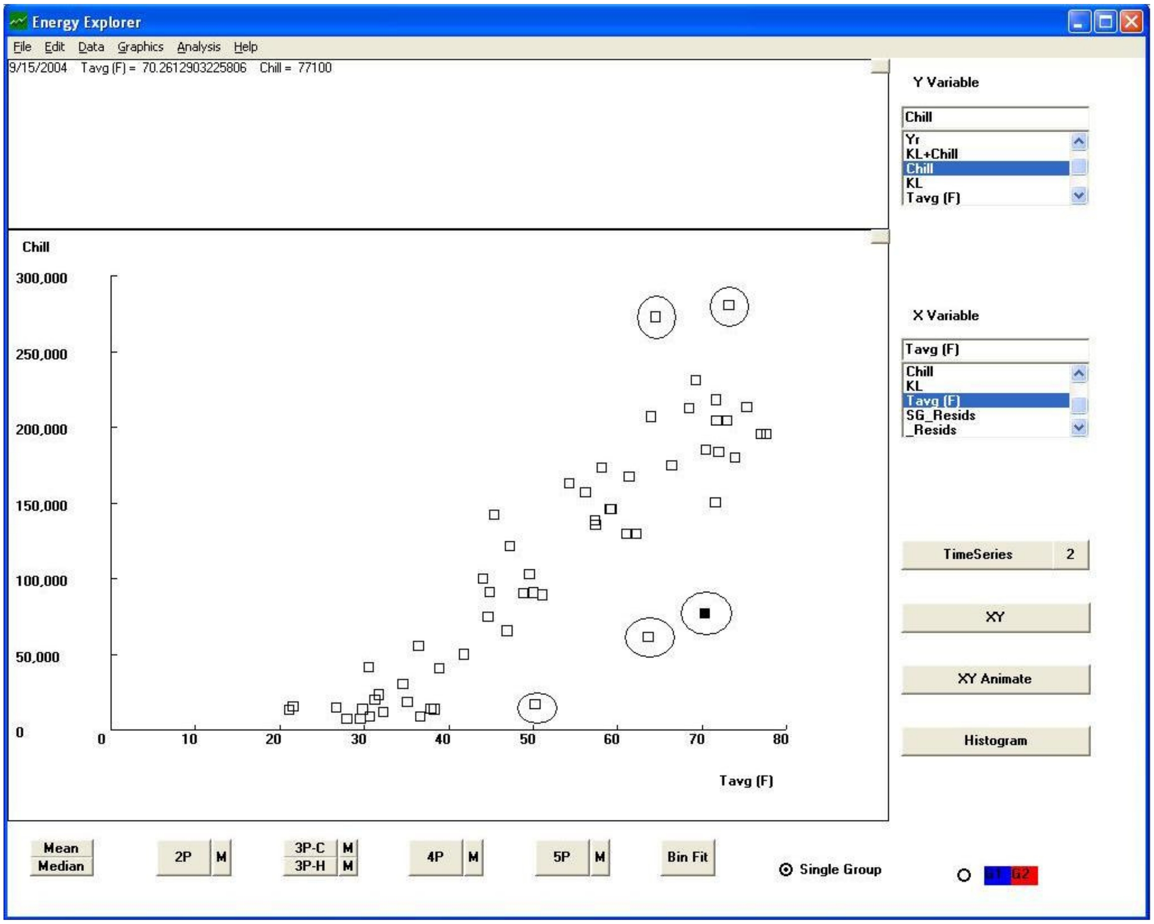

Figure 3. Monthly KL chiller electricity use plotted against average monthly outdoor air temperature.

After removing the outlying data points, the remaining data points were fit with a three-parameter change-point (3PC) model of chiller electricity use versus outdoor air temperature (Figure 4). The R^2 of the model is 0.91 with a RSME of 22,165 kWh/month. A second (3PC-MVR) model of chiller electricity use as a function of outdoor air temperature and whole-building electricity use was also developed. However, the fit of this model was not significantly better than the 3PC model. This indicates that whole-building electricity use does not appear to be a significant independent variable. Thus, the 3PC model is used to characterize typical baseline chiller electricity use, KLC (Equation 3).

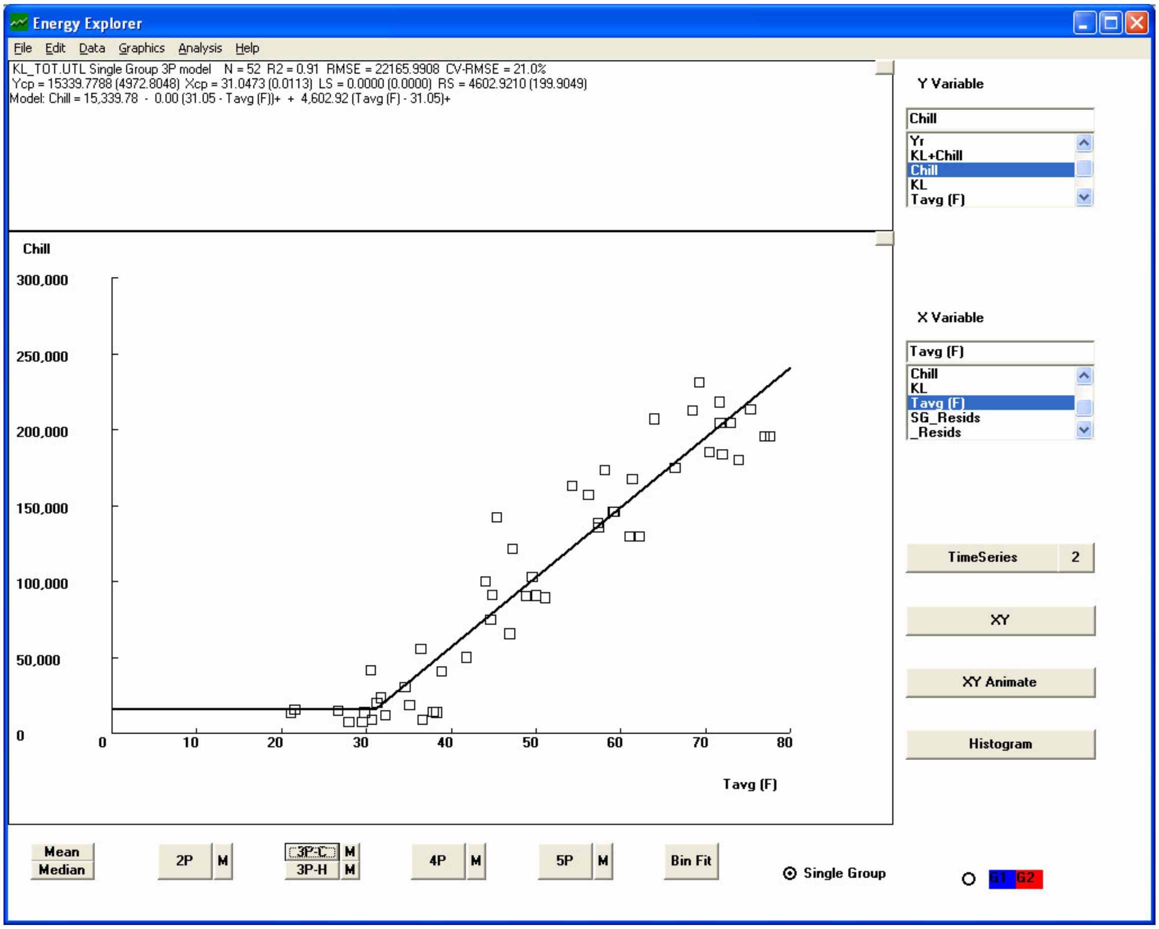

Figure 4. Monthly chiller electricity use plotted against average monthly outdoor air temperature with 5 outlying data points removed, and three-parameter cooling model.

$$KLC = 15{,}340 \text{ kWh/mo} + 4{,}603 \text{ kWh/mo-F } (T - 31.05 \text{ F})^{+} \quad (3)$$

Total baseline electricity use, KL, is taken to be the sum of the building and chiller electricity use. The model for total baseline electricity use, KL, is given in Equation 4.

$$KL = KLB + KLC \quad (4)$$

$$KL = (12{,}022 \text{ kWh/day x DPM days/mo}) + 15{,}340 \text{ kWh/mo} + 4{,}603 \text{ kWh/mo-F } (T - 31.05 \text{ F})^{+}$$

$$KL = 381{,}019 \text{ kWh/mo} + 4{,}603 \text{ kWh/mo-F } (T-31.05 \text{ F})^{+}$$

A file of typical total electricity use was created using the equation above and typical average monthly temperatures from the Dayton, OH TMY2 file. No electrical demand or steam use data are available for calibration. The resulting file, KL.UTL, is shown below.

KL.UTL

mo	dy	yr	elec	elec dmd	Fuel
12	31	2005	-99	-99	-99
1	31	2006	388022	-99	-99
2	28	2006	352416	-99	-99
3	31	2006	427884	-99	-99
4	30	2006	464470	-99	-99
5	31	2006	519438	-99	-99
6	30	2006	556760	-99	-99
7	31	2006	581072	-99	-99
8	31	2006	565514	-99	-99
9	30	2006	533331	-99	-99
10	31	2006	483304	-99	-99
11	30	2006	421616	-99	-99
12	31	2006	388022	-99	-99

Table 3. Data file KL.UTL with baseline total building plus chiller electricity use. -99 is a flag indicating that no data are available.

III. Simulated Baseline Energy Use

A model of current baseline building electricity and gas use was created using the ESim hour-by-hour energy simulation software (Kissock, 1997) and TMY2 data for Dayton, Ohio (NREL, 2007). The model uses the window areas shown in Table 1 and the window properties for double-glazed aluminum-frame windows shown in Table 2. Air infiltration through the windows was estimated using the air leakage rates calculated above. Based on those calculations, the rate of air infiltration though all 306 windows into Kettering Labs, which has a total air volume of about 1,320,000 ft^3, was estimated to be about:

$$3.23 \text{ ft}^3\text{/min-win} \times 306 \text{ win} \times 60 \text{ min/hr} / 1{,}320{,}000 \text{ ft}^3 = 0.4 \text{ air changes per hour}$$

The model was calibrated to baseline electricity use. Simulated and baseline electricity use are shown in Figure 5. Simulated electricity use shows good agreement with the baseline data; annual simulated electricity use is within 0.2% of baseline electricity use. Simulated natural gas use by boilers supplying steam to the building is shown in Figure 6. Although no baseline fuel use data were available for calibration, it is understood that the steam supply to the building is shut off during summer months. Thus, the simulation model was calibrated so that simulated fuel use was also zero during summer months. The building description input file for ESim is included in the appendix.

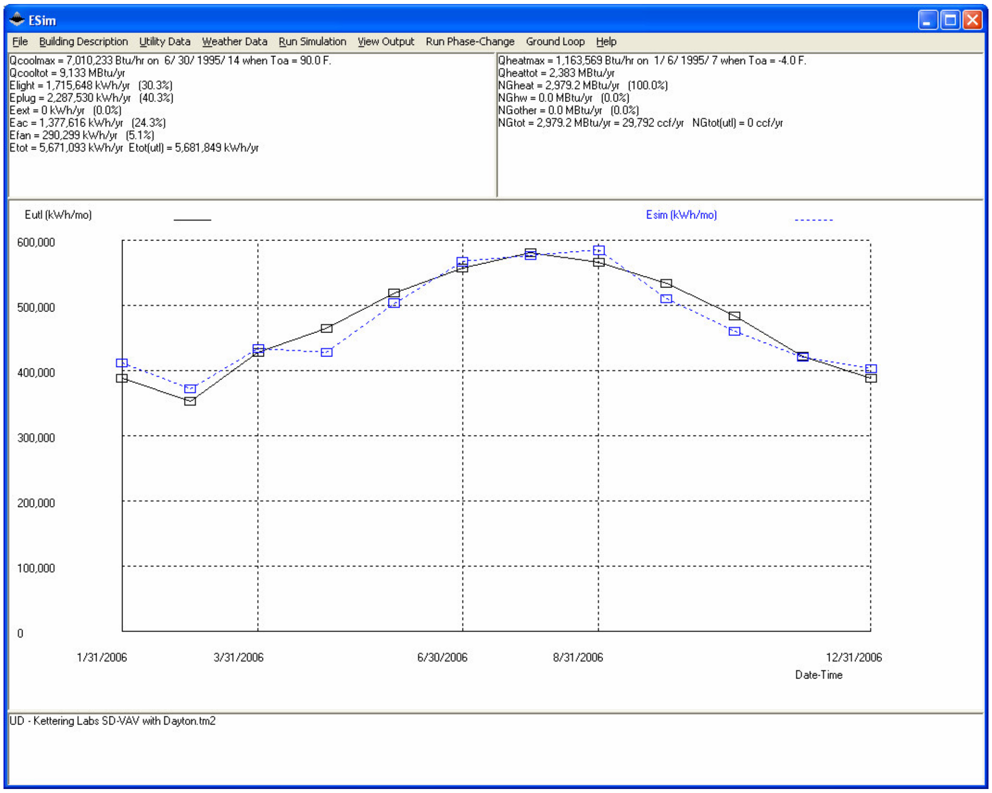

Figure 5. Simulated and baseline KL electricity use, including chiller electricity use.

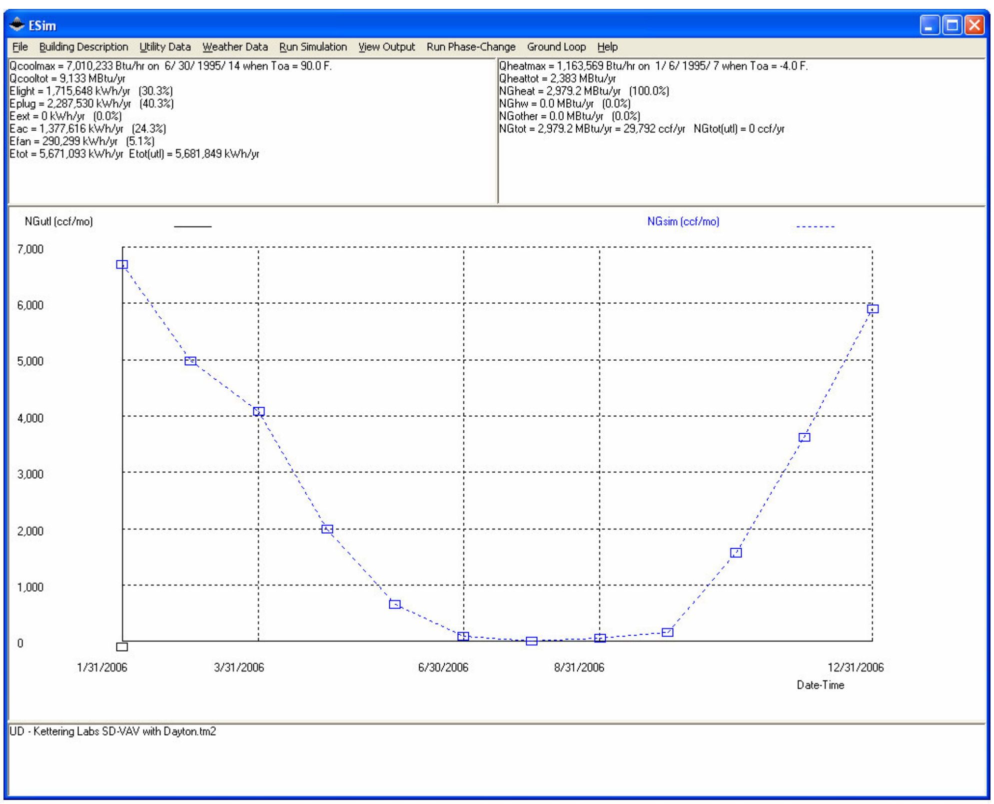

Figure 6. Simulated fuel use by boilers supplying steam to KL.

IV. Simulated Energy Use with Proposed Windows

Next the building description file for the baseline simulation model was changed to simulate building energy use with the proposed windows. The only changes to the building description file were to assume that infiltration through windows was eliminated, and to adjust the U values and SHGCs of the windows as shown in Table 2.

V. Anticipated Savings

Savings are estimated as the difference between the simulated electricity, E, and fuel use, F, of the baseline building, Base, and the simulated electricity and fuel use of the post-retrofit building, Post, with the proposed windows. Annual savings results are summarized in Table 4. Electricity cost, EC, savings were estimated assuming an electricity cost of $0.10 per kWh and fuel cost savings, FC, were estimated assuming a natural gas cost of $10 /mmBtu. Based on these simulations, anticipated cost savings from replacing the current windows with Pella double-glazed wood-frame windows are expected to be about $4,600 per year. Anticipated energy cost savings from replacing the current windows with Pella low-e double-glazed wood-frame windows are expected to be about $5,500 per year.

Proposed Window	Base E	Base F	Post E	Post F	Esav	Fsav	ECsav	FCsav	TCsav
	kWh/yr	mmBtu/yr	kWh/yr	mmBtu/yr	kWh/yr	mmBtu/yr	$/yr	$/yr	$/yr
Pella 3mm + 3mm	5,671,093	2,979	5,659,946	2,634	11,147	345	1,115	3,450	4,565
Pella 3mm + 3mm low e	5,671,093	2,979	5,657,216	2,568	13,877	411	1,388	4,110	5,498

Table 4. Summary of anticipated savings.

To facilitate an economic analysis of the first cost of the windows compared to the expected energy cost savings, the net present value, NPV, of the energy savings over the lifetime of the windows is estimated. The lifetime of the windows, n, is assumed to be 30 years. According to University officials, the real discount rate, i, for the University of Dayton is 5% (Mertz et al., 2005). From 1996 to 2005, the real cost of natural gas supplied by Dayton Power and Light and Vectren to the Dayton market increased by an average annual rate of 8.0%. Over that same period, the real cost of electricity supplied by Dayton Power and Light to the Dayton market decreased by an average annual rate of 1.2% (Mertz et al., 2005). From Table 4, natural gas savings make up about 75% of the total savings and electricity savings make up about 25% of the total savings. Thus, the local weighted real energy cost escalation rate, e, from 1996 to 2005 is about:

$$(75\% \times 8.0\%) + (25\% \times -1.2\%) = 5.7\%$$

The present value, P, of an escalating series of n annuities, A, with a real discount rate, i, and real escalation rate, e, is (Kissock, 1995):

$$
P = \begin{cases} A \dfrac{1}{(i-e)}\left[1-\left(\dfrac{1+e}{1+i}\right)^{n}\right] & \text{if } e \neq i \quad [5a] \\ A \dfrac{n}{(1+e)} & \text{if } e = i \quad [5b] \end{cases}
$$

Using Equation 5 and the values of A, i, e and n discussed above, the net present values of energy cost savings over the lifetime of the windows are shown in Table 5. Assuming a real energy cost escalation rate of zero, the net present value of energy savings is about $70,000 for the double-glazed windows and $85,000 for the low-e double-glazed windows. Assuming the same real energy cost escalation rate as from 1995 to 2005, the net present value of energy savings is about $143,000 for the double-glazed windows and $172,000 for the low-e double glazed windows.

	e = 0%		ε = 5.7%	
	A $/yr	NPV $	A $/yr	NPV $
Pella 3mm + 3mm	4,565	70,175	4,565	143,155
Pella 3mm + 3mm low e	5,498	84,518	5,498	172,413

Table 5. Net present values of energy cost savings over the 30 year lifetime of the windows for real energy cost escalation rates, e, of 0% and 5.7%.

Dayton Power and Light generates about 1.96 lb CO_2 per kWh of electricity generated (NRDC, 2006). The combustion of natural gas generates about 113 lb CO_2 per mmBtu of gas (US EPA, 2000). Using these coefficients, the CO_2 emission reductions are shown in Table 6.

	E Sav kWh/yr	F Sav mmBtu/yr	CO_2 Sav tonne/yr	CO_2 Sav tonne/30yr
Pella 3mm + 3mm	11,147	345	23	691
Pella 3mm + 3mm low e	13,877	411	28	832

Table 6. Expected electricity savings E Sav, natural gas fuel savings, F Sav, and CO_2 emission reductions, CO_2 Sav. (1 tonne = 2205 lbs)

References

Blevins, Jim, 2007, Personal communication.

Efficient Windows Collaborative, 2007, http://www.efficientwindows.org.

U.S. Environmental Protection Agency, 2000, Office of Global Climate Change.

Groesbeck, Leslie, 2007, Personal communication.

Kissock, K., 1995, “Time Value of Money”, http://www.engr.udayton.edu/faculty/jkissock/http/EEB/420main.htm, University of Dayton, Dayton, Ohio.

Kissock, K., 1997, ESim hour-by-hour building energy simulation software, http://www.engr.udayton.edu/faculty/jkissock.

Kissock, K., 2004, Energy Explorer data analysis software, http://www.engr.udayton.edu/faculty/jkissock.

Mertz, G. A., Raffio, G. S., Kissock, K., 2005. “Economic Analysis of the UD Eco-house: A New Era of UD Housing” Technical Report for Eco-house Economic Justification to UD Department of Residential Services and University Chief Financial Officer, Department of Mechanical and Aerospace Engineering, University of Dayton, Dayton, Ohio.

National Renewable Energy Laboratory, 1995, User Manual for TM2s, http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2/

National Resources Defense Counsel, 2006, “Benchmarking Air Emissions of the 100 Largest Power Producers in the United States – 2004”, http://www.nrdc.org/globalWarming/depth.asp.

Pella, 2005, Architectural Design Manual, Volume II, pages 3-3, 6-4 and 6-8.

Pella, 2007, Architectural Design Manual, Division 08 - Openings, page C11.

UD-EPA Average Daily Temperature Archive, 2007, http://www.engr.udayton.edu/weather/, University of Dayton Building Energy Center, Dayton, Ohio.

Appendix

KetLabs.MZB Building description file for baseline ESim simulation

```
"Building ID"                    "UD - Kettering Labs"
"INTERIOR TEMP SET POINTS========================"
"Occupied period start hour (1-24)"              8
"Occupied period end hour (1-24)"               22
"Occupied period days/week (0-7)"                5
"Occupied set-point temp (F)"                   72
"Unoccupied set-point temp (F)"                 72
"ROOF============================================"
"East-West ceil length (ft)"                   220
"North-South ceil length (ft)"                 150
"Max attic height (0 for flat roofs) (ft)"       0
"Ridgeline: EW, NS, none"                   "none"
"Solar absorbtivity of roof: 0 to 1.0"          .5
"Rroof+ceil (hr ft2 F / Btu)"                   10
"Rooftype: attic, steel, 2in-con, 6in-con" "6in-con"
"WALLS==========================================="
"Rwall (hr ft2 F / Btu)"                      4.37
"Solar absorbtivity of walls: 0 to 1.0"        0.7
"Wall type: steel,frame,block,12in-con"    "block"
"Awall n (ft2)"                               9549
"Awall s (ft2)"                              10141
"Awall e (ft2)"                               6707
"Awall w (ft2)"                               6510
"DOORS==========================================="
"Rdoors (hr ft2 F / Btu)"                     2.56
"Adoors (ft2)"                                   0
"WINDOWS========================================="
"R center-of-glass (hr ft2 F / Btu)"           1.32
"Area glass north (ft2)"                       1558
"Area glass south (ft2)"                       1451
"Area glass east (ft2)"                        991
"Area glass west (ft2)"                        1416
"Solar heat gain coef(normal,beam): 0 to 1"   0.68
"Bldg's rotation from true NSEW (degrees)"       0
"Average ground reflectance (0 to 1.0)"         .2
"WINDOW OVERHANGS AND WINGS======================"
"Protusion of overhang (ft)"                     0
"Gap between overhang and window (ft)"           1
"Height of window (ft)"                          5
"Protusion of wing (ft)"                         1
"Gap between wing and window (ft)"               1
"Width of window (ft)"                           6
"GROUND-COUPLING================================="
"Type: slab; hbase; unhbase"               "hbase"
"Floorweight: wood;3in-con;8in-con"      "8in-con"
"Perim (ft)"                                   740
"Afloor (ft2)"                               33000
"Rfloor (hr ft2 F / Btu)"                     2.89
"Rperim-insul (hr ft2 F / Btu)"                  0
"INFILTRATION===================================="
"Infiltration (air changes per hour)"           .04
"Volume conditioned area (ft3)"            1320000
"HOT WATER======================================="
"Vol HW (gal/hr)"                                0
"Temp HW (F)"                                  140
"Eff HW Heater"                                0.7
"MZB INTERNAL LOADS AND ELEC USE================="
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"Occupied light load (W/ft2)"                        1.5
"Occupied plug load (W/ft2)"                           2
"Occupied num people"                                400
"Eoccupied / Eunoccupied"                              4
"OTHER ENERGY CONSUMPTION=========================="
"Exterior elec cons (kWh/mo)"                          0
"Other ng cons (ccf/mo)"                               0
"MZB AIR HANDLING SYSTEM==========================="
"Conditioned floor area (ft2)"                    223610
"Fraction interior floor area"                       .95
"Air handler fan power (hp/1000ft2)"                1.21
"Maximum air flow rate (cfm/ft2)"                      1
"Minimum fraction outdoor air"                        .4
"Heating coil air exit temp (F)"                     120
"Cooling coil air exit temp (F)"                      50
"System type: DD-CAV;DD-VAV;SD-CAV;SD-VAV" "SD-VAV"
"Minimum air flow rate if VAV (cfm/ft2)"              .1
"HD-Reset: On; Off; Optimize"                      "Off"
"Economizer: On; Off"                               "On"
"MZB COOLING AND HEATING EQUIPMENT================="
"Cooling plant type: chiller or ac"           "chiller"
"If ac, SEER of air cond (Btu/hrW)"                   10
"Chiller size (ft2/ton)"                             447
"Nominal chiller efficiency (kW/ton)"              1
"Chiller part-load coefficient a"                  1.508
"Chiller part-load coefficient b"                 -1.917
"Chiller part-load coefficient c"                  1.439
"Heating plant type: boiler or hp"              "boiler"
"If hp, HSPF of heatpump (Btu/W-hr)"                 8.3
"Boiler size (input Btu/hr/ft2)"                      25
"Nominal boiler efficiency (%)"                       .8
"Boiler part-load coefficient a"                   .3307
"Boiler part-load coefficient b"                   .8402
"Boiler part-load coefficient c"                   -.161
"Chilled water pump power (hp/ton)"                  .10
"Chilled water pump: CS; VS"                        "CS"
"Condensor water pump power (hp/ton)"                .05
"Cooling tower fan power (hp/ton)"                   .05
"END CODE=========================================="
"End code"                                           -99
```