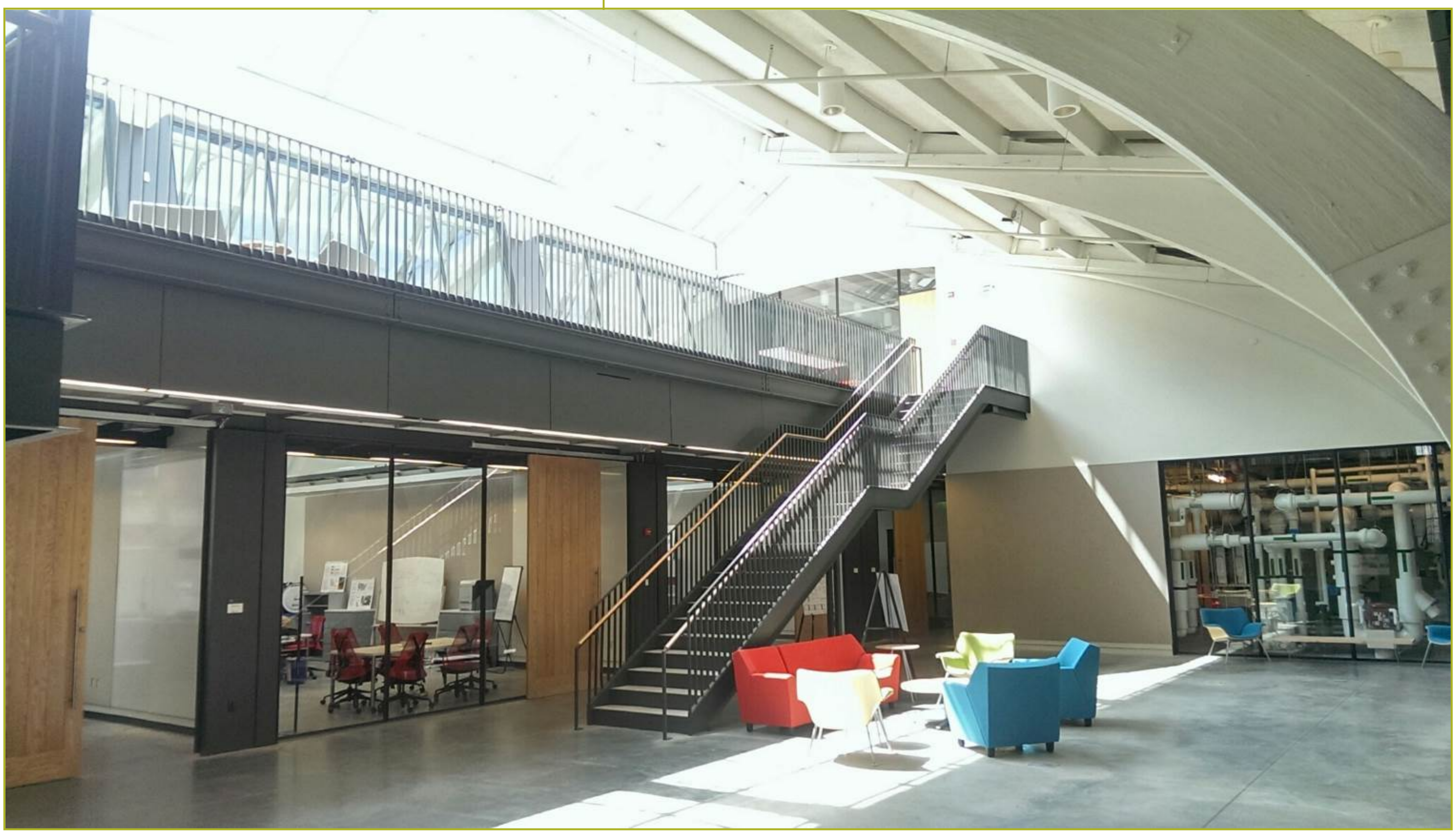
CONSORTIUM for BUILDING ENERGY INNOVATION

REPORT

Title: Demonstration of new lighting, HVAC, window, enclosure, control, or other technologies to reduce building energy use while improving indoor air quality

Report Date: January 2013

Report Author(s): Dr. Timothy Wagner



CBEI was referred to as the Energy Efficiency Buildings HUB at the time this report was developed.

Report Abstract

CBEI conducted modeling and demonstrations to evaluate multiple technologies, including air movement strategies, ultraviolet germicidal irradiation, hybrid ventilation and under floor air distribution, ventilation and shading systems, impact of roof color and roof insulation, lighting and shading controls and devices, high performance glazing, roof retrofit technologies, photosensor controlled electric lighting, and swirl diffusers.

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Disclaimer

Energy Efficient Buildings Hub

REPORT

Budget Period 2
SubTask 5.4
Deliverable #24 Report

Deliverable and Status

Task 5			
Subtask	**BP2 SOPO Deliverable Number**	**Task Deliverable**	**% Complete**
5.4	#24	Demonstration of at least five new lighting, HVAC, window, enclosure, control, or other technologies to reduce building energy use while improving indoor air quality	100%

- Subtask Leader/Organization: Tim Wagner/UTRC
- Task Performer(s)/Organization(s):

Subtask	Title	Performer(s)	Organization(s)
5.4	EEB Subsystems Demonstration	Amy Wylie Erica Cochran Michael Waring Jim Yorgey Seong Lee Pat Athey Keith Rule Elie Bou-Zeid Bill Bahnfleth Quingyan Chen Thanos Tzempelikos Rick Mistrick Azizan Aziz	Bayer MaterialScience CMU Drexel Lutron Morgan State PPG PPPL Princeton PSU Purdue Purdue PSU CMU

Executive Summary

Ten EEB Hub performer organizations contributed to the successful completion of deliverable #24: Demonstration of at least five new lighting, HVAC, window, enclosure, control, or other technologies to reduce building energy use while improving indoor air quality. The technologies demonstrated were:

1. **Air Movement Strategies** – Drexel PI Waring conducted a demonstration through simulation of dynamic ventilation and outdoor air (OA) movement strategies. The modeling analysis included the indoor air quality (IAQ) effects and energy saving potential. The focus was on four potentially high impact, relatively low cost Advanced Energy Retrofits (AERs) using off-the-shelf technologies: supply air temperature (SAT) reset, economizer operation, demand controlled ventilation (DCV), and exhaust air heat recovery (HR). EnergyPlus models of offices that are typical of the ten-county region were used to assess every combination of these technologies. The research objectives were to recognize any destructive or synergistic interaction effects and to identify the building vintages and HVAC systems for which these AERs are best suited.

2. **Ultraviolet Germicidal Irradiation (UVGI)** – An annual simulation of a 10,000 ft^2 representative office building in the Philadelphia area was used to show that the effects of mitigating biofouling resulted in over 14% savings in fan and pump energy.

3. **Hybrid Ventilation and Under Floor Air Distribution (UFAD)** - Hybrid ventilation was demonstrated through simulation by Purdue; results showed 20 -38% annual cooling electricity energy saving in the Philadelphia region for typical small to medium sized office buildings. An Under Floor Air Distribution (UFAD) system was also demonstrated through simulation and experiment in test facilities on energy uses and IAQ. Results showed that a UFAD system can consume less energy in chilling than well-mixed system in the Philadelphia region and will increase IAQ by 25% in terms of contaminant exposure compared with that for a well-mixed system.

4. **Ventilation and Shading Systems** – A hybrid ventilation system and extensive night cooling experiments were conducted from May to October 2012 in the Intelligent Workplace (IW), a lived-in laboratory of high performance building systems, at Carnegie Mellon University. A rule based algorithm was developed for natural ventilation and implemented in the IW for 6 months in the spring/summer/fall 2012. Over the six-month period, hybrid ventilation can be implemented for 21% of the time, resulting in 15% savings in cooling energy while maintaining an indoor relative humidity between 40%-50%. The CMU research team also conducted a series of occupied laboratory experiments at the IW to assess the impact of aluminum venetian blind shading and external light redirection devices on internal air and radiant temperatures as well as light levels. Blinds at different tilts and orientation provided different energy savings. On the south side, maintaining closed blinds can provide up to 12% cooling load reduction with blinds at fully closed position and 4% reduction with blinds at 45^0 tilt. However 45^0 tilt blinds offer the benefits a partial view to the outside and increased light levels in the space.

5. **Impact of Roof Color and Roof Insulation on Building Energy** – PPPL and Princeton demonstrated the energy performance impact of different roof colors and insulation through measurements made on instrumented roof sections on four different roofing systems at PPPL.

6. **Lighting and Shading Controls and Devices** – A Purdue Test Facility consisting of two identical insulated and airtight 20ft x 20ft test office spaces with reconfigurable façade and lighting systems was used to demonstrate automated shading and lighting systems. The results showed energy savings (up to 60%) compared to no lighting controls, depending on the shading type and control strategy used. Energy savings (reduced cooling demand) from shading devices and controls ranged from 5% to 30% depending on the shading and glazing used and window size.

7. **High Performance Glazing (HPG)** – PPG demonstrated the energy saving benefits of HPG (Solarban® 60 glass, Solarban® 70XL glass, Solarban® R100 glass, Solarban®z50 glass, and combinations of Solarban and Sungate® 600 glass products in RENOVATE BY BERKOWITZ™) in Philadelphia using a 4F DOE office building (aspect ratio-

AR=1.5, window to wall ratio-WWR=40% and 0^0 orientation-50% more glass facing N&S) "simulation building" using DesignBuilder and EnergyPlus. In the "simulation building" HPG options provided total building energy savings of 8-14% and cooling savings of 14-18%. Building orientation affects energy usage; in the "simulation building" total energy savings is minimized at 0^0 orientation. When HPG is used total energy savings vary 1.2% (buildings oriented from 0^0 to 135^0) while it varies 4.3% for clear-clear glazing. Thus, choosing HPGT for a retrofit building offers improved energy savings and less dependence on its orientation. PPG demonstrated HPG energy saving benefits for a 2F Building 669 (AR=5.8, 90^0 orientation, 88% glazing facing E & W) of 15% total energy savings and 28% cooling savings when monolithic glass was the baseline and 6% and 9%, respectively when a tint-clear glazing was the baseline.

8. **Roof Retrofit Technologies** – Roof retrofit technologies within an integrated roof system were analyzed and ultimately demonstrated through simulation based on the impact of each component on the overall energy consumption of the simulated building. Roof components that had the largest impact on increased efficiency (Energy Use Intensity, EUI) while affecting the largest number of buildings were selected for demonstration. The major roof components demonstrated in BP2 were:
   - Increased roof Insulation
   - Improved Roof Membrane System
   - Skylight & Glazing System

   Selected roof demonstration findings and results were incorporated into a guidebook "Integrated Roofing Retrofits: High Performance Integrated Flat Roofs and Skylights" (Cochran, E; Loftness, V; Aziz, A; Mokashi, M; Kolosky, A: Hodari, S). The guidebook provides a summary of multiple integrated roof technologies that have the opportunity to save at least 20% of a building's energy while promoting a total building integrated retrofit.

9. **Photosensor Controlled Electric Lighting** – Demonstrated in Computer Models - Penn State investigated the performance of single-zone and multi-zone photosensor-based lighting control systems in spaces with windows (sidelighting) using computer models of the daylight and electric light distributions in spaces. A comparison of the potential energy savings of these systems showed that optimized multi-zone control utilizing smaller control zones can provide increased energy savings over a large single zone system. A multi-zone control system offers a more challenging calibration and layout condition, however, this study showed that a sequential multi-zone control system can greatly simplify both the control algorithm and system calibration, and deliver near optimum multi-zone performance.

10. **Swirl Diffusers** – The research team at Morgan State University has designed and fabricated a swirl diffuser; this will be demonstrated as part of a hybrid ventilation system prototype in BP3.

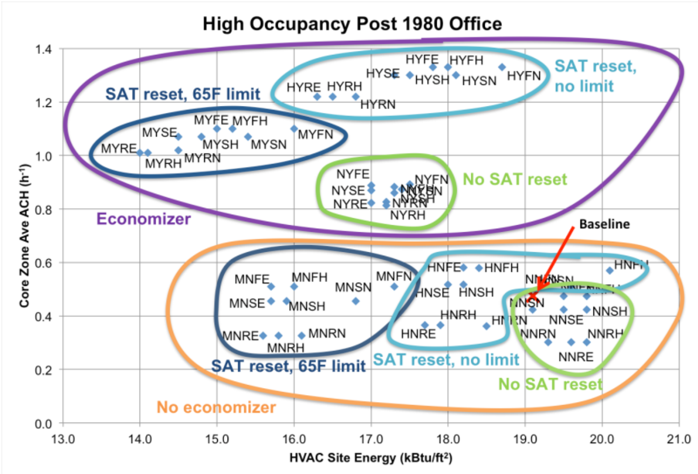
Narrative

1. Air Movement Strategies

Drexel PI Waring conducted a demonstration through simulation of dynamic ventilation and outdoor air (OA) movement strategies. The modeling analysis included the indoor air quality (IAQ) effects and energy saving potential. The focus was on four potentially high impact, relatively low cost Advanced Energy Retrofits (AERs) using off-the-shelf technologies: supply air temperature (SAT) reset, economizer operation, demand controlled ventilation (DCV), and exhaust air heat recovery (HR). EnergyPlus models of offices that are typical of the ten-county region were used to assess every combination of these technologies. The research objectives were to recognize any destructive or synergistic interaction effects and to identify the building vintages and HVAC systems for which these AERs are best suited.

Results indicated a clear choice for a first implementation priority as an AER: a combined package of SAT reset and economizer control. Economizer control significantly improved annual IAQ in the ten-county climate, representing a win-win strategy. Annual HVAC site energy savings were sensitive to building type. For buildings with multizone VAV systems, they were 15% in a recent vintage building and 16% in a circa 1980 building, with about half the savings coming from the economizer and about half from SAT reset. In these multizone VAV buildings, the two technologies combined well, with SAT reset enhancing the economizer's IAQ benefits by allowing it to operate a greater percentage of the time (Figure 1). Energy savings were 8% in a pre-1980 building with single zone packaged CAV systems, all from economizer implementation since the baseline package units already modulated SAT. The 59% savings in the pre-1980 building with a multi-zone CAV system came mostly from SAT reset since the baseline control strategy, with its constant volume and SAT with reheat operation, was extremely wasteful. An implication is that deep energy savings are likely available by targeting the fraction of buildings that have these types of systems, and implementing an inexpensive control strategy change in them. The other two technologies did not have as dramatic effects, and should as a rule be considered after SAT reset and economizer control are in place. For the pre-1980 multizone CAV building, neither technology had an appreciable effect. For the other buildings, adding DCV or HR *each* decreased HVAC energy use further by between 5%-10%, leading to total combined savings between 22% and 35%. The Drexel team is currently working with Task 8 to identify candidate buildings for BP3 implementation of these AERs and validation of the simulation findings, and also plan to conduct measurement and verification (M&V) of these AERs in Building 101.

In BP2 Dr. Waring's team also began conducting an assessment of more advanced supervisory OA control, leveraging dynamic effects and considering IAQ and energy impacts at the same time. As a first step, a case study was conducted by simulating an office for which all parameters were known. Initial results were promising, especially for core zones and in the winter, where HVAC energy savings were on the order of 40% without significant IAQ degradation.



Key (read from bottom up):

N N F N

- **Heat recovery:**
  - N = none
  - H = heat (sensible)
  - E = enthalpy
- **DCV:**
  - F = fixed (none)
  - R = R_p only (reduce 17 cfm/occ)
  - S = Sum (reduce 5 cfm/occ)
- **Economizer:**
  - N = no
  - Y = yes
- **SAT reset:**
  - N = none (constant 55 °F)
  - M = medium (reset w/ max of 65 °F)
  - H = high (reset w/ max of 120 °F [essentially no max])

Figure 1 Different combinations of readily available HVAC technologies can help save energy, increase ventilation, or provide both benefits, but their interaction effects can be complex. Simultaneously plotting the energy and IAQ performance of each combination (each point on this scatter plot) helps identify strategies that improve both objectives**.**

2. Ultraviolet Germicidal Irradiation (UVGI)

The objective of this project is to demonstrate the use of ultraviolet germicidal irradiation (UVGI) of cooling coils in HVAC systems for the purpose of reducing energy use by controlling microbial growth on the wetted coil surface. Performance is being predicted via annual simulations using data on fouling from the literature. Two field test demonstration sites outside greater Philadelphia will be ready to begin operation in BP3 and a third site is being sought in Philadelphia.

Simulation

An annual simulation of a 10,000 ft^2 representative office building in the Philadelphia area was created to examine the effects of biofouling (and its mitigation) on building energy use. A single constant air volume (CAV) and single zone variable air volume (VAV) system were examined. Both were served by chilled water coils with constant speed pumps. Given the scant literature on typical biofouling effects on coil heat transfer and airside pressure drop in real building operation, data from a recent laboratory study was used to modify clean systems into fouled systems (Pu, H., et al. 2010. "Air-side heat transfer and friction characteristics of biofouled evaporator under wet conditions." Front. Energy Power Eng. China. 4(3):306 – 312).

For the CAV system, elimination of fouling saved 1.3% in fan energy and 14.8% in pump energy. The result of the fan energy is expected, as increasing the pressure drop on a CAV system simply shifts the system curve so there is less airflow but also *less* power consumed. The slight increase in energy use is due to increased fan run hours. The pump energy result indicates that the decreased heat transfer coefficient of the cooling coil results in a decreased waterside dT, which then necessitates an increased pump flow to meet loads. For the VAV system, elimination of fouling saved 14.7% in fan energy and 15.2% in pump energy. In this case, the fan motor had to expend more power for the same airflow because of the fouling. The increase in pump energy was again due to the increased water flow rate needed to meet load.

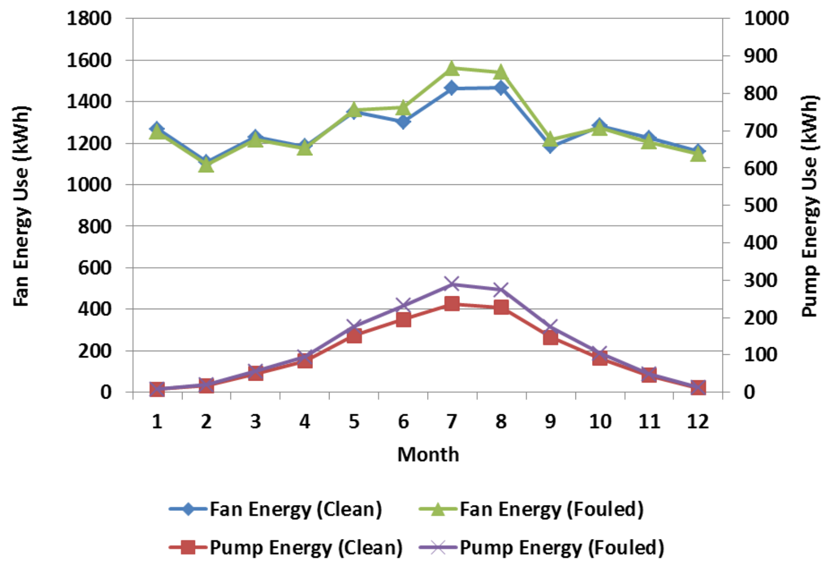
However, these percentage savings need to be put in context. As Table 1 shows, the fan energy expenditure is higher than the pump energy. Saving fan energy results in a greater economic effect, and VAV systems appear to be a more suitable target for savings. It is worth noting that CAV systems seem to be on the decline in new construction, but may still be present in existing buildings.

Table 1 – Yearly Clean vs. Fouled Component Energy Use

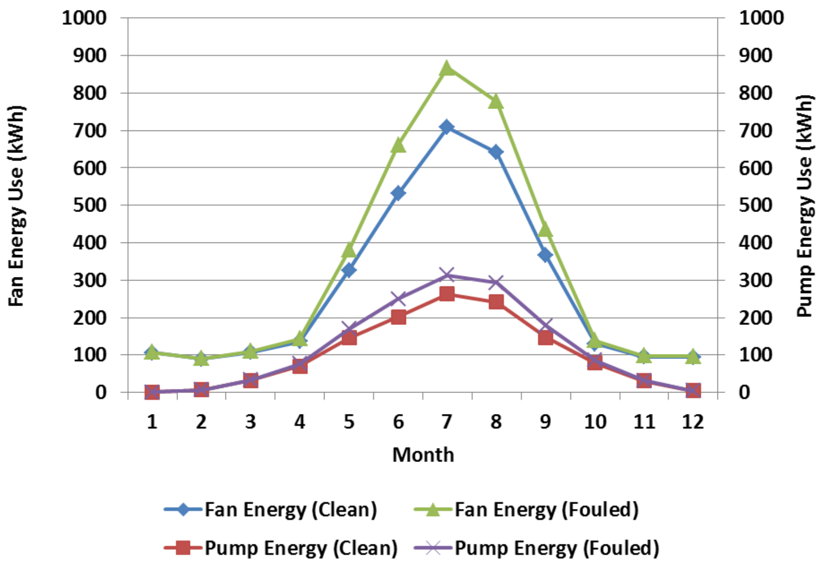
	CAV Fan	CAV Pump	CAV Total	VAV Fan	VAV Pump	VAV Total
Clean Coil (kWh)	15,223	1,266	16,490	3,333	1,223	4,556
Fouled Coil (kWh)	15,419	1,487	16,906	3,907	1,442	5,349
Energy Saved (kWh)	195	220	416	574	219	793
Energy Saved (%)	1.3%	14.8%	2.5%	14.7%	15.2%	14.8%

In Figure 2, the monthly energy over the course of a year indicates that the savings seem to be realized more over the summer for both system types.

Progress in BP3 will use actual data from a Penn State site, a Tampa site, and a planned Philadelphia site (search currently underway) to provide more realistic parameters for the modeling of fouled coils, in addition to analysis via life cycle costing.



(a)



(b)

Figure 2 – Effect of coil fouling on component energy use for a (a) CAV and (b) VAV air system

Field Demonstration

Installation of measurement equipment at the site in Tampa, FL was started near the end of BP2 and will be complete during January 2013. This is a full scale building demonstration, and data will be collected and analyzed during BP3. Photographs detailing some of the progress are shown in Figures 3-12. Installation of a second, similar system at the Penn State University Park campus is expected to be complete during February 2013. Both systems will be operational and collecting data during the 2013 cooling season. These installations include coil irradiation systems designed according to typical industry practice and instrumentation that will collect data needed to assess the impact of UVGI on fan and cooling plant energy consumption: air and water flow rates, air moisture content, coil entering and leaving air and water temperatures, pressure drop across the cooling coil. In addition, biological sampling is being conducted to determine the impact of UVGI on the microbiome of the air-handling unit.

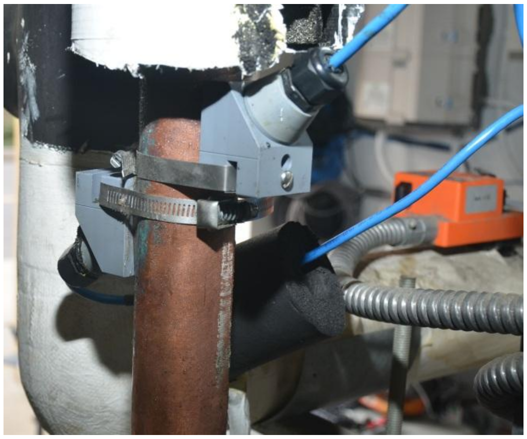


Figure 3 – Installed ultrasonic water flow meter in Z-formation

Figure 4 – UV lamp interlock with door

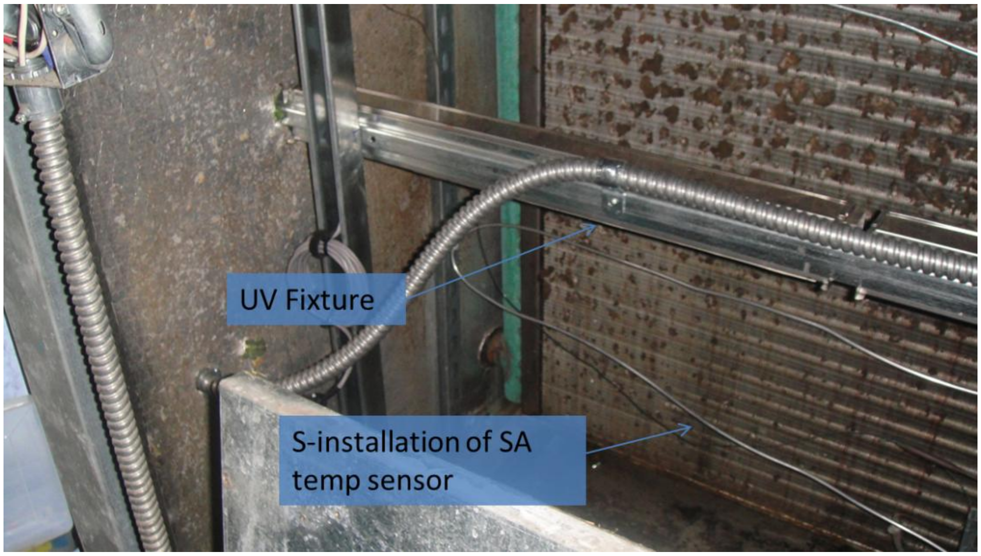


Figure 5 – Downstream side of coil

Figure 6 – UV lamps and downstream side of coil

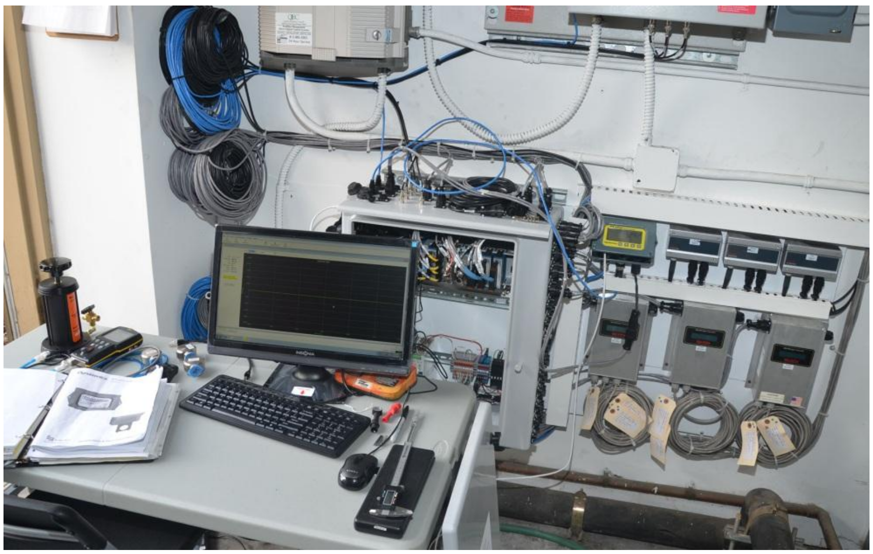


Figure 7 – Setup at Tampa site during testing of installation

Figure 8 – Data collection

PSU Site

Assembly of equipment and data-logging enclosure for the PSU site is underway and almost complete. Pictures below detail the progress.

Figure 9 – Machining of custom enclosure

Figure 10 – Completed custom enclosure (note extra room and ports for expansion)

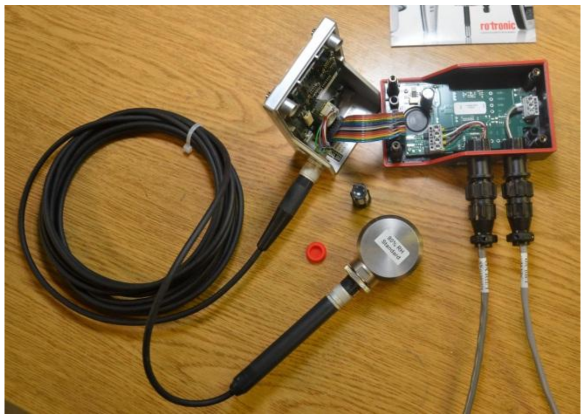


Figure11 – Configuration and calibration of RH sensor

Figure 12 – Testing of ultrasonic flow meter at PSU site

3. Hybrid ventilation and Under Floor Air Distribution (UFAD)

Purdue developed several control strategies that prioritize humidity control for natural ventilation in the Philadelphia region. The results showed that, when using humidity oriented control, the hours when relative humidity is above 80% were decreased by 15%-21% compared to temperature oriented control for small and medium offices. However, there are still too many dissatisfaction hours when using natural ventilation along in Philadelphia region due to high humidity and high temperature. Therefore, hybrid ventilation is recommended to satisfy the thermal comfort need.

Purdue demonstrated hybrid ventilation with night cooling strategy in Philadelphia through EnergyPlus simulations on typical small and medium office buildings. The hybrid system was compared with a constant air volume (CAV) rooftop unit and found up to 30% cooling energy savings. The model was based on a small office building with three rooftop units for mechanical cooling. Hybrid ventilation with night cooling strategy was implemented from May 1st to Sept 30th. The building construction was based on ASHRAE 90.1 (2007) for baseline study. Another retrofit case studied used a concrete thermal mass between the insulation layer and the inside gypsum board in the exterior wall. Such retrofits increased the thermal storage during night cooling thus further reducing the energy consumption in the hybrid ventilation case. The baseline case shows 30% cooling electricity saving with the hybrid ventilation compared to that with mechanical system. The retrofit case shows 38% cooling electricity savings compared to the baseline mechanical system case. Both the mechanical system and hybrid system used the same setpoint temperature to ensure that thermal comfort was not compromised in exchange for energy savings. For the medium office buildings, since the core zone cannot be naturally ventilated, the energy saving by using hybrid ventilation was lower than small offices, but can still achieve 20% of cooling electricity saving with retrofit on the wall and floor compared to baseline mechanical system case. (Figure 13)

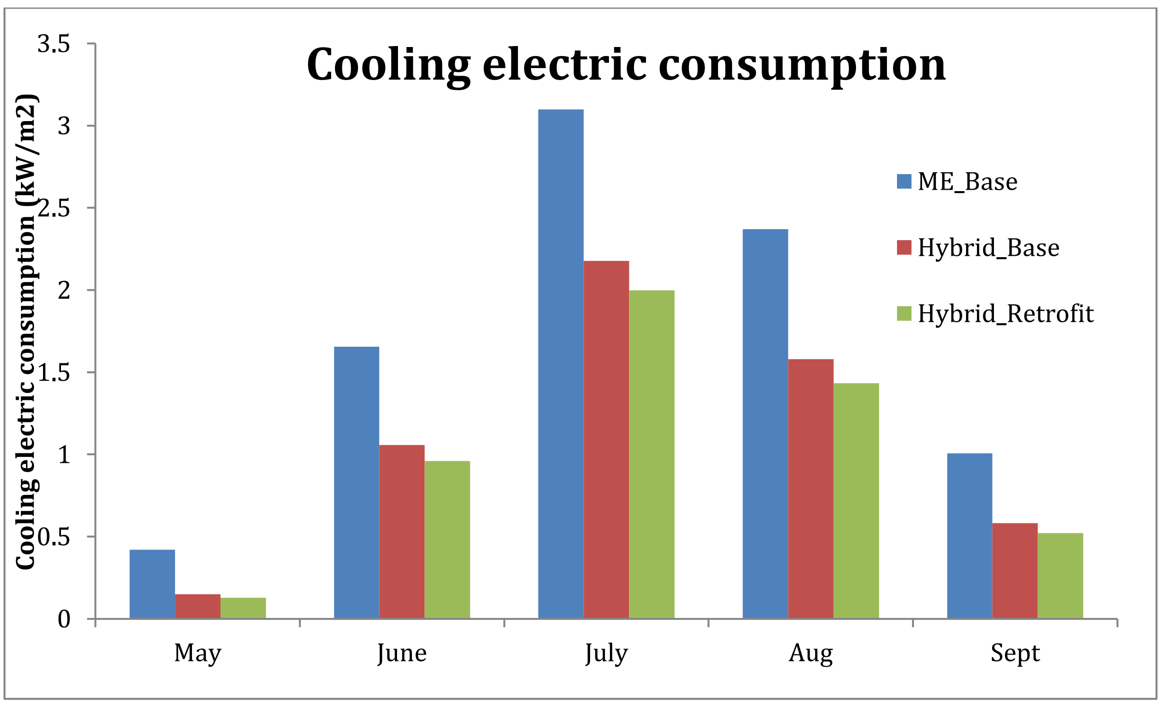


Figure 13 Monthly cooling electric consumption for mechanical system, for hybrid system without retrofit on the thermal storage, and for the hybrid system with retrofit on the thermal storage

Demonstration of a UFAD system was conducted at Purdue's environmental chamber; EnergyPlus simulations of annual energy use and IAQ were also conducted. Thermal storage and heat transfer between the floor and ceiling plenums was investigated. In summer during daytime, low air temperature in the floor plenum leads to heat transfer from the ceiling plenum downstairs to the floor plenum that increased supply air temperature from the floor diffusers. This process resulted in a higher cooling load of the building with the UFAD system compared with a well-mixed system. In the evening, however, the building with UFAD systems had a lower cooling load due to the cool floor slab. The total cooling load of building with the UFAD system was 5% higher than that with the well-mixed system for the summer design day in Philadelphia. Nevertheless, a higher supply air temperature in the UFAD system allowed more free-cooling time. Thus, the annual energy consumption by chiller for the UFAD system was 10% less than that for the well-mixed system in Philadelphia. However, the UFAD would consume more heating energy. In terms of IAQ, Purdue conducted an experiment in an environmental chamber with a contaminant source from occupants. Under these conditions, UFAD showed 25% less contaminant exposure than the well-mixed system (Figure 14).

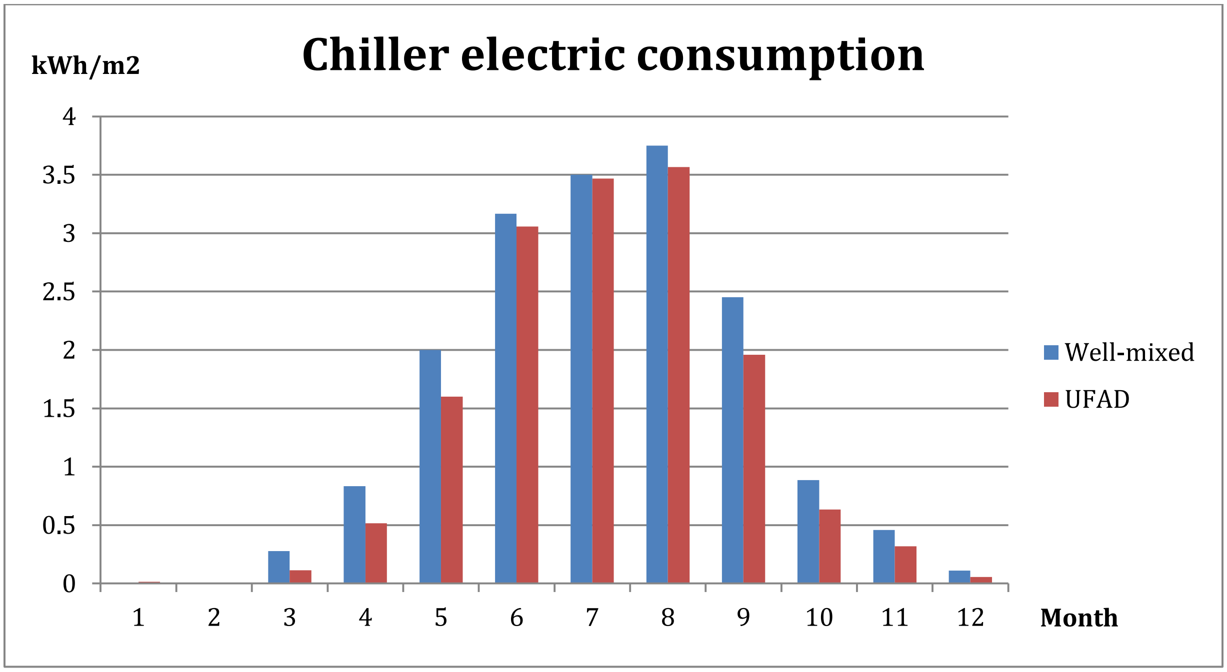


Figure 14 Monthly chiller electrical energy consumption for a medium office building with the well-mixed and UFAD systems in Philadelphia

Purdue has developed a more accurate and easy-to-use model for predicting natural ventilation rate. The model was validated by existing experimental data and CFD simulations with ±20% accuracy (Figure 15). Purdue also developed a new model that includes both fluctuating velocity and eddy penetration effect on the ventilation rate for wind driven, single-sided natural ventilation. The governing equation is based on the non-uniform pressure distribution along the opening height. The results show that the mean ventilation rate and mean velocity are linearly correlated. The benefit of linearity is used to further study the eddy penetration effect in frequency domain based on Fast Fourier Transform (FFT). Large Eddy Simulation (LES) and experimental data are used to validate the new model and results shows good agreement. A further design analysis based on the model is presented to provide guidelines for building design on window geometry and building orientation to maximize the ventilation rate. The ventilation rate model was integrated in EnergyPlus for natural and hybrid ventilation study to achieve better accuracy.

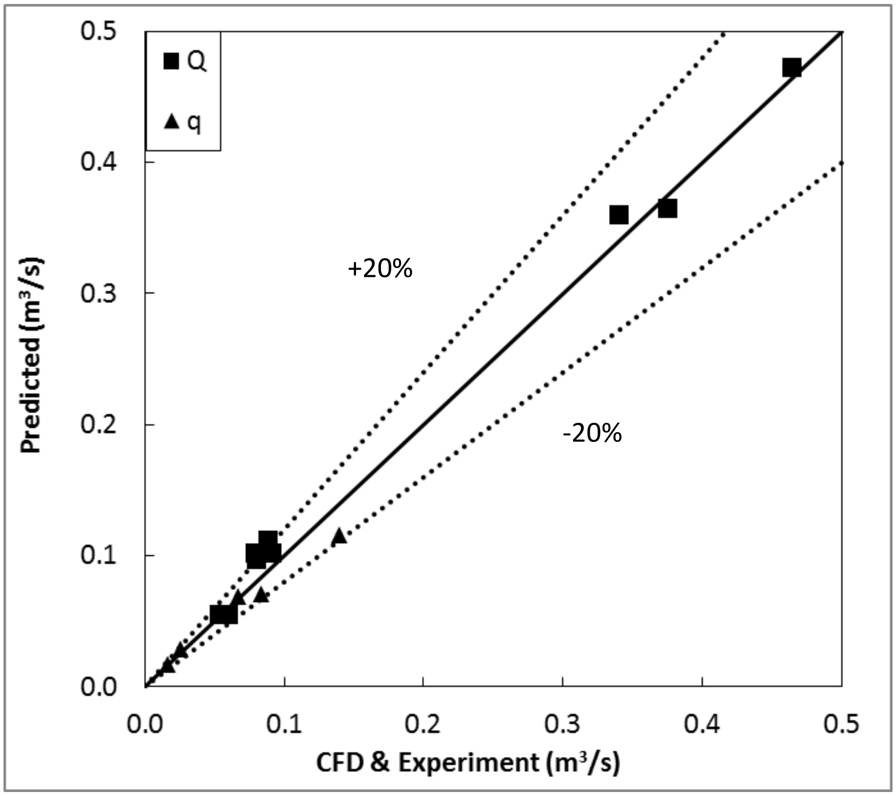


Figure 15 Comparison of predicted ventilation rate with CFD and measured ventilation rate (Q stands for mean ventilation, q stands for fluctuating ventilation rate)

4. Ventilation and Shading Systems

Hybrid ventilation experiments were conducted in the IW at CMU for six months, from May to October. From Table 2, windows were opened 8% of the of the time in the month of July, even with temperatures peaking at 99^0F and averaging at 77.2^0F. In addition, temperatures in July were above 80^0F for 35% of the time. During that month windows were open 30% of the time during occupied hours. In August, windows were opened 16% of the time and almost a quarter of the time during May and June. In September and October, windows were opened more than 25% of the time.

Table 2: The percentage of open windows during the months of May, June, July and August, September and October 2012.

	Hours of natural ventilation	*%Open*	*% of the time*	*Ratio Day/Night*	
May	162 h	**22%**	9%	39%	Day time
			13%	61%	Night time
June	175 h	**25%**	5%	20%	Day time
			20%	80%	Night time
July	63 h	**8%**	2.5%	30%	Day time
			5.5%	70%	Night time
August	116 h	**16%**	8%	50%	Day time
			8%	50%	Night time
September	186 h	**26%**	13%	50%	Day time
			13%	50%	Night time
October	199 h	**28%**	15%	54%	Day time
			13%	46%	Night time
6 Months	903 h	**21%**	9%	42 %	Day time
			12%	58 %	Night time

Over the 6 months of experiments, automated operable windows opened for a total of more than 900 hours (21% of the time). The combination of daytime and nighttime ventilation and cooling strategies led to the reduction of cooling loads by 15%.

Extensive night cooling ventilation using manually operated windows was also tested for several nights in the summer of 2012. During the night of June 25th, 80% of the operable windows in the IW were opened. The temperature impact of this intervention was compared to 2 similar outdoor night temperature conditions, one where just the transom windows were opened (6th - 7th June), and another where all windows were closed (13th – 14th June) (Figure 16).

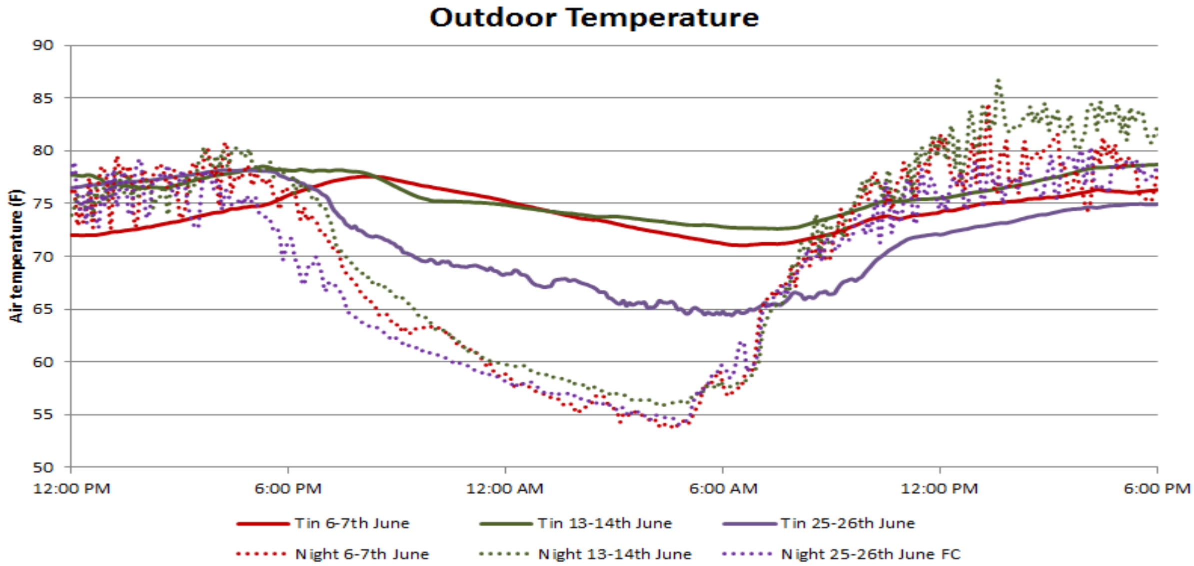


Figure 16: 3 days of similar night outdoor temperatures were selected for comparison.

The free cooling impact is represented in light blue (Figure 17). Up to 5°F free cooling was achieved with the extensive intervention. The indoor temperature remains lower throughout the day of the extensive ventilation study. Compared to opening automated windows, this intervention maintained a 2^{0}F lower temperatures and almost 5^{0}F lower temperatures compared to all closed windows.

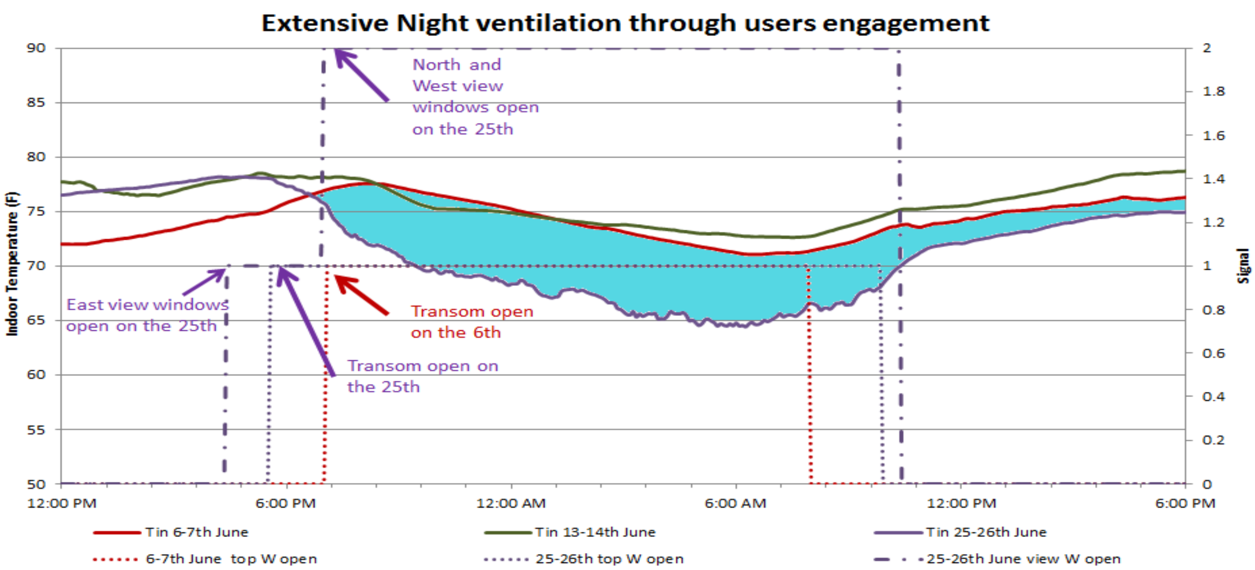


Figure17 : Temperature comparisons of 3 different interventions, all windows closed, all transom windows open, 80% of all windows open

The research team also conducted a series of occupied laboratory experiments to assess the impact of aluminum venetian blinds on internal air and radiant temperatures as well as light levels. Significant findings of ambient and radiant differences between open and closed blinds in the south east bay for almost identical days - in terms of average outdoor temperatures, clear sky solar radiation levels, no mechanical heating, and low interior occupancy conditions - reveal:

- Closing blinds on a day with outdoor temperatures rising from 50-65°F (8 am-6 pm), will maintain 2°F cooler morning indoor ambient air temperatures, and 8°F cooler peak radiant temperature conditions during the morning.
- Opening blinds at night allowed 3°F of free cooling through radiation to the night sky.

Note: Interior ambient temperatures without conditioning ranged from 68-74°F with daylight levels of 100-150 lux when blinds were closed.

The experiments also reveal that setting south and east blinds to a better shading position at a 45° tilt will reduce air temperatures by 1-2°F as compared to blinds set horizontally (Figure 18). Daylight levels were sustained at 200 lux for effective ambient lighting. Radiant temperature differences were even more substantial which will also have energy and comfort impacts.

Note: The two days illustrated had comparable outdoor temperature and solar gain conditions. May 6 indoor temperatures were uniformly raised by 1.89° F to reflect average contribution of week day internal gains.

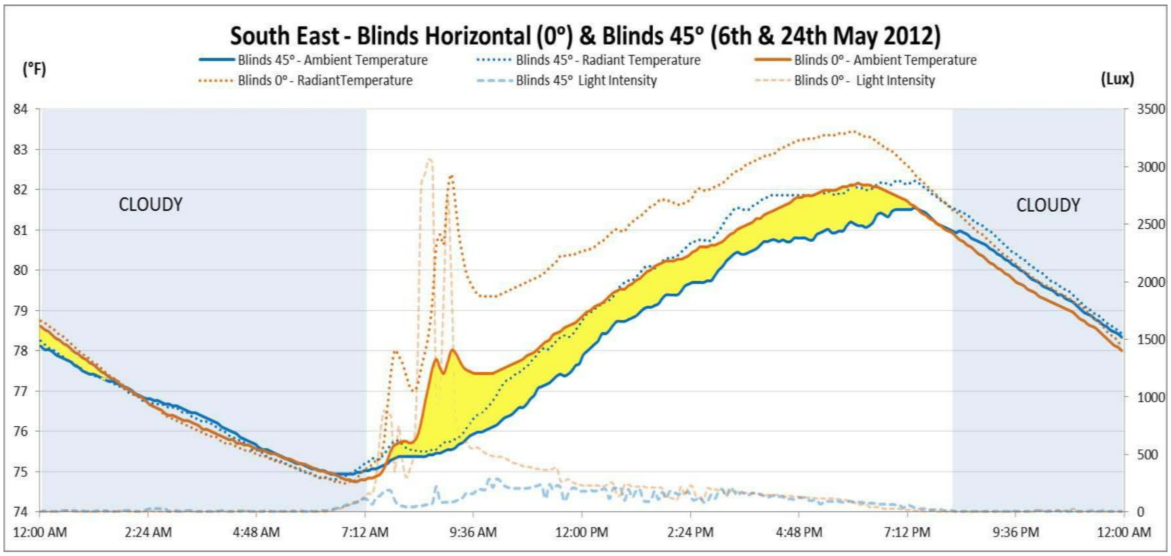
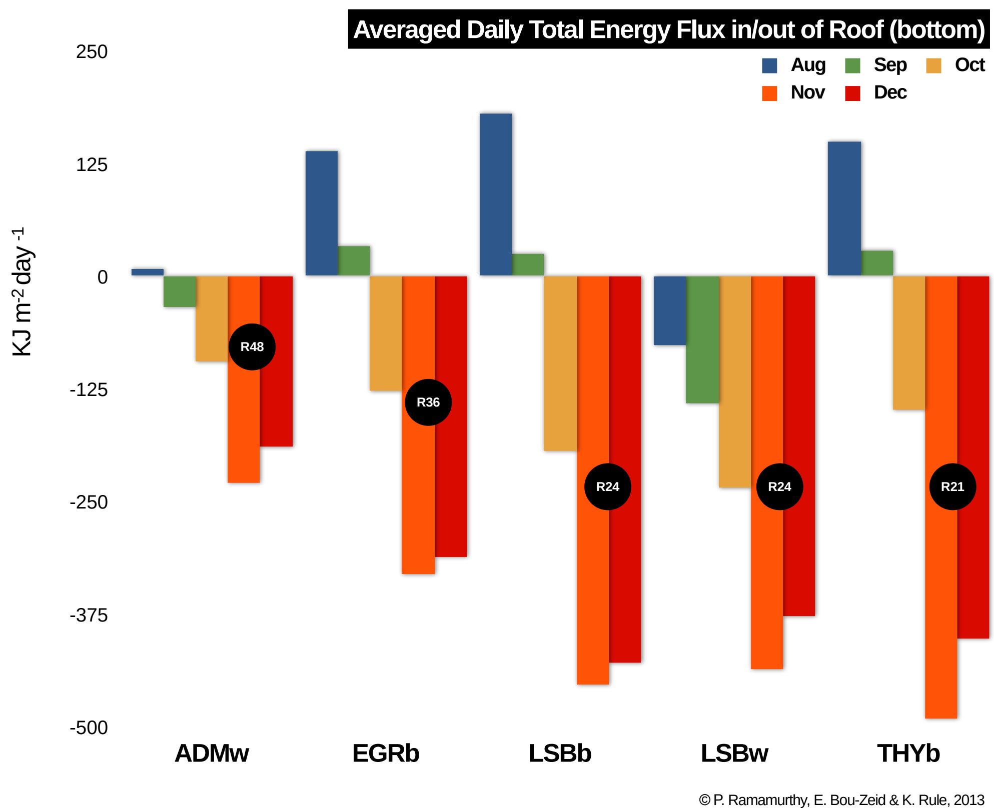


Figure 18: Ambient, radiant and light level differences between horizontal and 45⁰ tilt blinds in south east bay

5. Impact of Roof Color and Roof Insulation on Building Energy

PPPL and Princeton demonstrated the energy performance impact of different roof colors and insulation through measurements made on instrumented roof sections on four different roofing systems at PPPL. Figure 19 shows the averaged total flux of energy, per day per square meter that enters through the different roofs. The positive values indicate energy coming (hotter outside) in to the building while the negative values show the energy lost from the building (hotter inside). All the data shown in the figure were measured using high precision heat flux plates, placed at the interface of roof and the building ceiling.



ADMw = white R-48, EGRb = black R-36, LSBb = black R-24, LSBw = white R-24, THYb = black R-21

Figure 19 Averaged Daily Total Energy Flux in/out of Roof (bottom)

Overall, while the roof color plays a dominant role during the warmer months in controlling the energy entering the building, roof insulation is important during colder seasons to prevent heat loss. During warmer months (August and September), the white roofs do better in insulating the building. This is evident by their low or even negative values (ADMw and LSBw), which are better than black roofs with higher insulation. In the colder months, the effect of insulation is clearly visible: ADMw, which has a high R-value (48), performs very well in preventing energy loss through the building. Most losses in winter are visible in the least insulated roofs THYb (R21), LSBw (R24) and LSBb (R24).

In support of Deliverable 24, a roofing retrofit project was performed on one of the four flat roofs being measured and modeled. The roof on the Lyman Spitzer building was removed and replaced with a Carlisle 90 mil EPDM membrane with an average design insulation value of R-30. The total square footage of roofing was 33,000 ft2 with 29,000 ft2 being the Carlisle SureWhite Fleece backed 145 mil EPDM membrane and 4,000 ft2 with the 90 mil black EPDM membrane. This 4,000 ft2 was directly compared with an identical 4,000 ft2 of white membrane at diametrically opposed locations for energy flux and thermocouple readings.

If you reference Figure 19 and examine the R-24 roof energy flux values (LSBb & LSBw), one can derive clear conclusions. In August, the black membrane is allowing over 150 KJ/m2 per day to enter the building while the white membrane at Lyman Spitzer (LSBw) indicates a slight loss of energy from inside the building of 60 KJ/m2 per day. Also at the highly insulated white roof over ADM, the incoming energy is a meager 7.6 KJ/m2 per day.

Figure 19 also provides clear evidence of a small "penalty" for heat loss in the white membrane for the winter months. November 2012 had a slightly higher comparison for all roofs. In regard to the R-24 roof the energy flux (heat loss) difference between the black and white membrane is 25 KJ/m2 per day (~5%), indicating a low heat gain from the black membrane.

Four different roofing insulation values were measured at PPPL with a total of five locations; two locations with white membrane and three with black membrane. When referring to Figure 19, you can see a near-linear correlation in energy flux (heat loss) in the winter months. The R-24 black roof energy loss results indicate a 38% increase as compared to the R-36 black roof with an associated ratio of 66% R-24/R-36. The white roof membrane supports this further. The insulation values are 50% (R-48/R24 while the energy flux (heat loss) is 47% more for the R-24. The relationships are not as straightforward when there are heat gains due to the changes in radiative cycle and varied albedo, although it is clear that increased insulation provides benefit.

6. Lighting and shading controls and devices

Full-scale experimental studies conducted at Purdue demonstrated that continuous dimming of T5 HO lamps in both direct recessed and direct-indirect lighting settings provide significant energy savings (up to 60%) compared to no lighting controls, depending on the shading type and control strategy used. Lighting control algorithms for direct and direct-indirect (recessed) lighting systems were tested under various sky conditions and shading scenarios. Lutron's lighting control systems were used and customized control sequences were developed for maximizing lighting energy savings from the use of natural light. Energy savings through the use of roller shades and control were also demonstrated, with energy savings (reduced cooling demand) ranging from 5% to 30% depending on the shading and glazing used and window size. Full-scale demonstration since the beginning of BP2 has shown significant advantages of employing efficient shading controls in both reducing cooling energy use and reducing glare problems for occupants. Two different roller shades (existing products) have been compared and six different control algorithms for roller shades were demonstrated to investigate their impact.

The results were used to validate developed models. Blinds, light-shelves and other systems have been shipped and are ready for testing in BP3.
Other efforts that will continue in BP3:

- Synchronized lighting and shading operation: the objective of this research is to demonstrate efficient and synchronized operation of shading and lighting in order to reduce energy use while maintaining thermal and visual comfort for the occupants. We have demonstrated and tested this concept at Purdue using the several developed algorithms.
- Glazing technologies: Glazing units with selective coatings (VUE coatings) are being tested and three types of glass are currently being installed in collaboration with PPG: clear-clear (reference case for existing buildings) and Solarban 60 and 70 for a comprehensive comparison and demonstration of energy savings and human comfort.
- The experimental set-up for mixed-mode cooling testing has been completed. The three-zone lab building has a curtain wall with integrated motorized vents and interior shading, as well as operable windows and it will allow testing of different climate control approaches (in collaboration with Kawneer and Functional Fenestration, Inc).

7. High performance glazing (HPG)

PPG demonstrated the energy saving benefits of high performance glazing (Solarban® 60 glass, Solarban® 70XL glass and Solarban® R100 glass, Solarban® z50 glass, and Sungate® 600 glass in RENOVATE BY BERKOWITZ™) in the Philadelphia region using DesignBuilder and EnergyPlus. A 4F office building using hourly climate data for Philadelphia with an aspect ratio of 1.5 (long axis oriented N-S; 50% more glass faces N & S (0°)) and a window to wall ratio (WWR) of 40% was used as the "simulation building". High performance glazing technology (HPGT) is defined as glazing that allows more daylighting into a building while reducing utility (heating, cooling, etc) and capital costs (HVAC sizing).

The first glazing simulation demonstration was completed using the "simulation building" and HPGT which was compared to clear-clear glazing baseline. HPGT can offer total building energy savings of 8% and cooling energy savings of 10-14%. Using argon gas rather than air in an insulated glazing unit (IGU) offers another 1% in energy savings. A buildings orientation affects its total energy consumption and thus its energy savings. HPGT shows less dependence on building orientation. For HPGT the energy savings with building orientation varies 1.2% from 0^0(=180^0) to 135° while it varies 4.3% for clear-clear glazing. Thus, 3% in energy savings is gained by choosing HPGT for this "simulation building". A second glazing simulation demonstration was completed using the same "simulation building" for a new window retrofit system RENOVATE BY BERKOWITZ™. This system turns low performance monolithic glass into a high-performance triple IGU without removal of the existing monolithic glass. The simulations used either a clear-air-Solarban 60 (4)-argon-Sungate 600(6) triple IGU or a clear-air-Solarban 70XL(4)-argon-Sungate 600(6) triple IG HPGT configuration vs clear monolithic glass. Total building energy savings were 12-14% while cooling energy savings were 15-18%. A third glazing simulation demonstration was completed for Building 669 with an aspect ratio of 5.8, clear monolithic glass at a 90^0 orientation (88% of glass facing E&W). Three glazing performers were recommended and used for subsequent integrated modeling. The energy savings contribution from glazing alone depends on the baseline windows. When the baseline case is monolithic glass the top performer offers total building energy savings of 15% and cooling savings of 28% versus 6% and 9%, respectively, when clear-tint glazing unit is the baseline.

The conclusion of this work is HPGT plays an important role in energy efficient retrofit projects. Compared to lighting, HVAC, and roofing technologies, which undergo retrofits more frequently than glazings, the optimal choice in glazing technology is important because the replacement cycle is typically between two and four times longer than other building technology systems. Based on the above simulation work, a subset of these glazing technologies was fabricated and shipped to Purdue for testing in BP3.

High Performance Glazing Recommendations for Philadelphia Region

A 4F DOE office building (N-S Long axis orientation, 1.5 Aspect Ratio, WWR=40%) was utilized to represent a retrofit building in the Philadelphia Navy Yard and is the "simulation building" in this work. A schematic of the "simulation building" is shown in Figure 20. EnergyPlus, a DOE supported building simulation software, was used with DesignBuilder as the GUI. Six high performance Low-E glasses using 6mm glass/13mm Air or Argon gap/6mm glass insulated glass unit (IGU) configurations were compared against a clear monolithic glass or a clear-clear IGU. The building specification in the building used ASHRAE 90.1-2010 standards. A summary of the input parameters utilized in the modeling in this report are shown in Table 3. Most buildings in the region were built with monolithic clear glass and do not meet ASHRAE 90.1-2010 building material standards. Thus, any comparison results in energy savings are less than would actually be observed with the existing building and are dependent on how fully a retrofit is completed.

Table 3 Summary of input parameters for simulation in a 4F DOE rectangular building in Philadelphia.

City	Philadelphia		Construction	
Climate	ClimateZone4		Ext Walls	0.592 W/m2-K
Matl Spec Standards	Ashrae 90.1-2010		Roof	0.273 W/m2-K
			Grd Floor	1.907 W/m2-K
Layout			Int. Floor	1.907 W/m2-K
Bldg	1.5 Aspect Ratio		Infiltration	0.255 ac/h
Length (m)	73.11			
Width (m)	48.74		Openings	
Height (m)	3.96		Clr Air Clr	2.68 W/m2-K
Orientation	0 deg		Low E Air Clr	1.611 - 1.645 W/m2-K
Total Bldg Floor m2	17804.9		WWR	40%
Activity			Lighting	
Occ. Load	0.05 people/m2		Lighting	11 W/m2
DHW	0.333 l/m2-day		Luminaire type	Suspended
Heat Setpoint C	21		Rad fraction	0.7
Heat Setback C	15.6		Visible fraction	0.2
Cool Setpoint C	24			
Cool Setback C	26.7		HVAC	
Equip Plug Load	11 W/m2		Heating	Gas fired condensing boiler
Rad Fraction	0.5		Cooling	Water cooled chiller

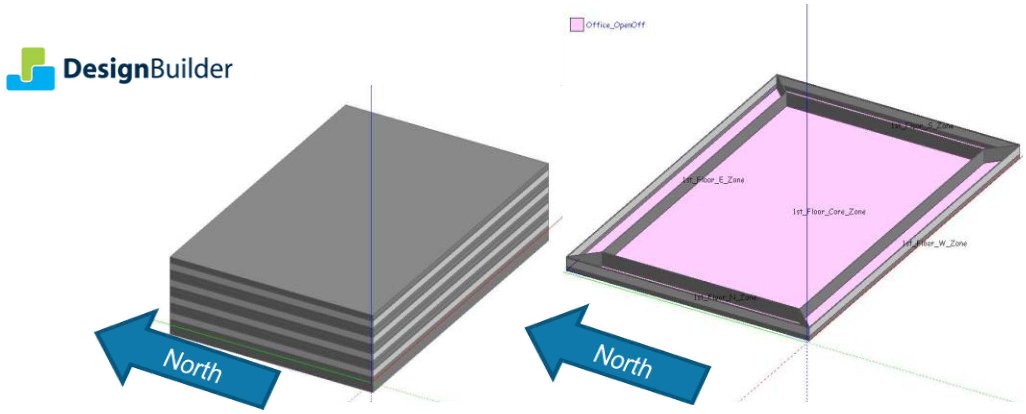


Figure 20 Schematic within DesignBuilder of the "simulation building" described in this work

The top glass performer is a highly reflective Low-E glass, Solarban® R100 glass, with total building energy savings of 281,461kWh/yr compared to a clear glass-air gap-clear glass unit. When the gap is changed from air to argon the energy savings are slightly higher at 299,271kWh/yr. The second, almost equivalent, performer Solarban 70XL glass offers higher visible light transmittance. The energy saving differences between SBR100 and SB70XL are seen in the percent cooling and heating savings they each offer as shown below in Figure 21. Solarban 70XL offers better heating savings while SBR100 offers better cooling savings. Total building energy savings, when *only glass* is changed, is 7.7% for an air gap using Solarban R100 glass and 7.5% using Solarban 70XL for this particular example. Note that lighting, equipment, and DHW consumption do not change with glass configuration, combined they contribute 46-50% of the total building energy. Thus, it is important to integrate lighting and shading technologies with glass technologies to fully optimize energy consumption in a building renovation.

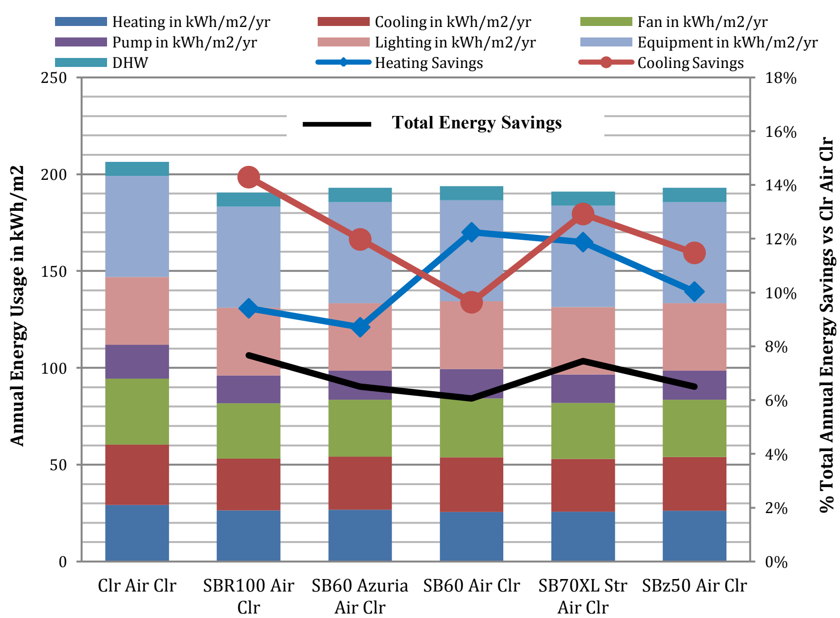


Figure 21 Building Energy Simulation using DesignBuilder and EnergyPlus of the Annual Energy Usage and savings for a 4F DOE building in Philadelphia for different glazing

New Glazing Retrofit Technology:

Substituting argon for air in the IGU (insulated glass unit) in this 4F DOE rectangular building in Philadelphia results in an additional 1% total building energy savings with the best savings coming from Solarban® R100 glass. Building materials specified in Table 3 and schematic shown in Figure 20 for this model are for a new building which is substantially better than for the existing (older) buildings in the Philadelphia region.

In the "simulation building" the total building energy savings is different for a clear-clear glass configuration than for high performance glass configurations as a function of building orientation. For purposes of this work, 0° orientation means that 50% more glass faces N & S for the 4F rectangular shaped building with an aspect ratio of 1.5. Similarly, a 90° orientation means there is 50% more glass facing in the E & W.

Graphing the building orientation vs the total annual energy consumption in the "simulation building" as a function of glass configuration in Figure 22 shows that building orientation has less of an effect on the total energy usage when high performance glass like Solarban® R100 glass is utilized. This is seen from a flatter Solarban R100 curve (Red Squares) as compared to the clear-clear case (blue diamonds). To better understand this effect we look to two key performance parameters of a glazing; its U_{value} and its SHGC. The U_{value} of a glazing is defined as its overall coefficient of heat flow and is an indication of its insulation capability. The solar heat gain coefficient (SHGC) of a glazing is an indication of how well it blocks solar heat gain. The U_{value} is low and roughly equivalent for each of the high performance glazings modeled while the less performing clear-clear has much higher U_{value}. The U_{value} (red +'s in Figure 23) curve is less correlated with total energy consumption curve.

For this "simulation building", the importance of SHGC can be seen in Figure 23 where the SHGC curve (green x's) correlates more closely with that of the energy consumption curves than does the U_{value} curve (red +'s). This does not mean that the U_{value} is not important but that SHGC is more strongly correlated with energy savings for "simulation building". To further generalize, more simulation work would be required. Note that the energy consumption curve vs glazing type has the same shape for all building orientations.

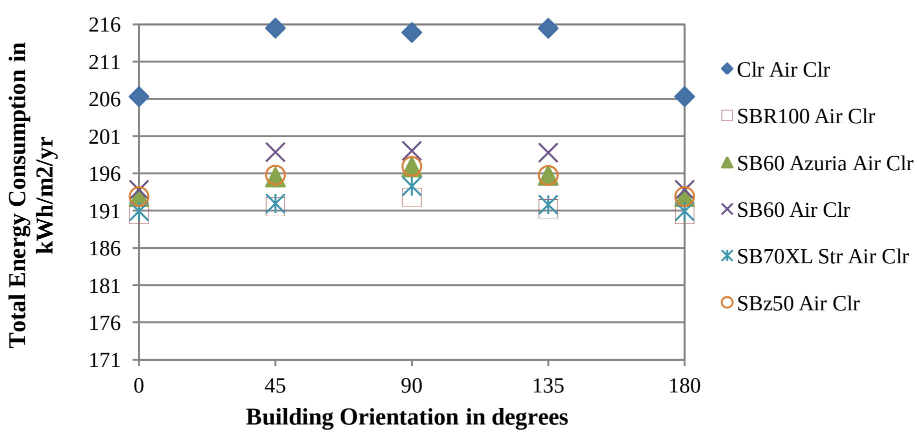


Figure 22 Total energy consumption versus building orientation for HPGT vs clear air clear glazing.

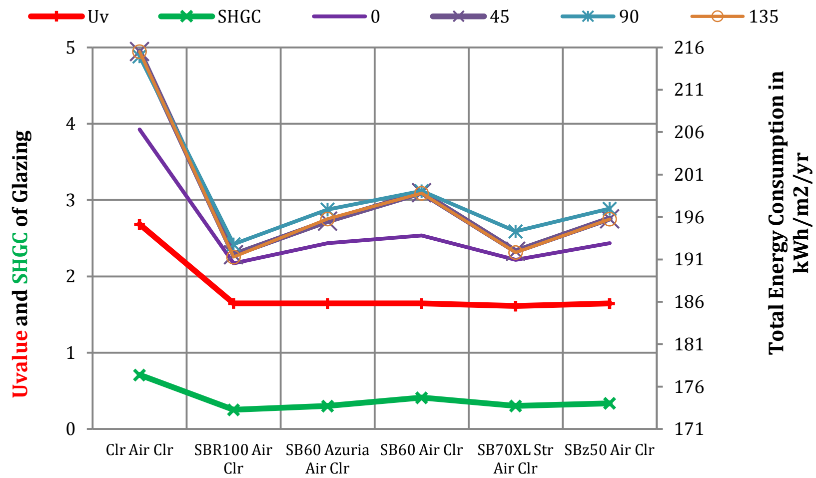
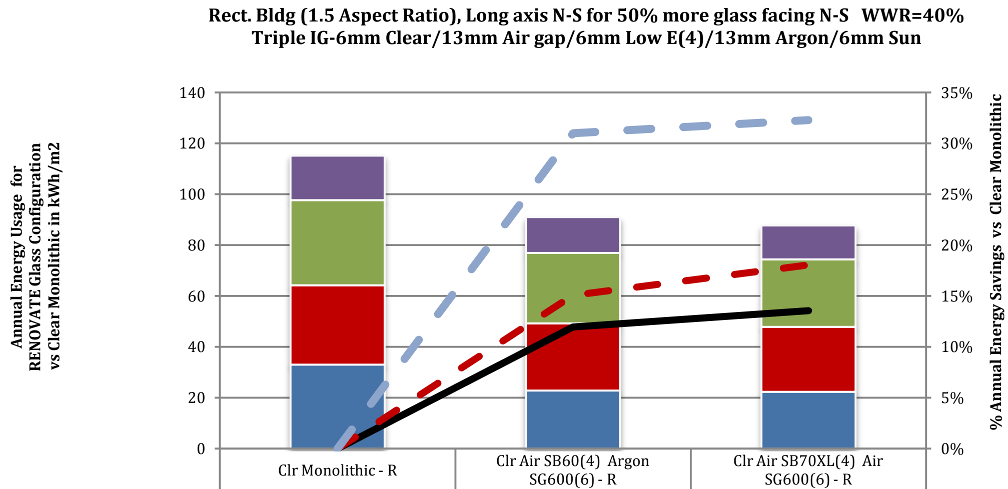


Figure 23 In this "building simulation" model the SHGC is more strongly correlated with Energy consumption than is the U_{value}.

A new window retrofit technology using HPGT was also modeled using building simulations of a 4F DOE rectangular shaped building. The technology is called RENOVATE BY BERKOWITZ™ (from JE Berkowitz a regional business) which converts a monolithic glass into a high performance triple IGU. A visit was made to Berkowitz to discuss the retrofit technology and proposed modeling work to demonstrate the energy savings. The chart and table in Figure 24 below shows the reduction in energy usage of heating, cooling, fan, and pump energy from using clear monolithic glass versus the RENOVATE technology which uses high performance Solarban® 60 (12% total energy savings) or Solarban® 70XL (14% total energy savings) along with a new HPGT product in 2012 known as Sungate® 600 glass. The total cooling energy savings for these two HPGT products versus monolithic glass are 15-18%.



	Clr Monolithic - R	Clr Air SB60(4) Argon SG600(6) - R	Clr Air SB70XL(4) Air SG600(6) - R
Pump	17.5	14.0	13.3
Fan	33.5	27.7	26.5
Cooling	31.1	26.4	25.5
Heating	33.0	22.8	22.3
Total Annual Energy Savings	0	12.0%	13.6%
Cooling Savings	0	15.1%	18.0%
Heating Savings	0	31.0%	32.3%

Figure 24 Building Energy Simulation of RENOVATE glass technology using DesignBuilder and EnergyPlus for a 1.5 aspect ratio rectangular 4F DOE building in Philadelphia

Building 669 Integrated Design:

PPG performed a second demonstration by simulation for Building 669 in the Philadelphia Navy Yard. Modeling work was further refined so that material data input was consistent with cross team discussions on the expected building parameters for the renovation. The improved building baseline input parameter for the external wall is $0.564W/m^2K$, for the external roof is $0.277W/m^2 K$, for adjacent walls is $1.022W/m^2 K$, for the ground floor is $3.265W/m^2 K$, and for the internal floor is 1.911 W/m2 K.

The U_{value} of the window ranges from $2.68W/m^2 K$ for the tint and clear window IG units to 1.64 to 1.61 for the low-E window units (note monolithic glass has $U_{value} = 5.8W/m^2 K$). The windows are modeled with thermally broken Aluminum frames. The building infiltration is set to 0.1 ACH, the occupancy load is 0.1people/m2, the plug load is 11W/m2, and lighting is 13W/m2. The heating is modeled using a gas fired condensing boiler and the cooling uses a VAV w/terminal reheat (ASHRAE 90.1-2010). For future work, the HVAC system will be further refined to be consistent with cross team discussions and to determine the variation in energy savings of glazing using different simulation techniques.

The DesignBuilder sketch-up was zoned as shown in Figure 25; the building schematics were based on drawings obtained from the owner. The windows in the 1F are modeled using the existing type of monolithic clear glass and additionally this floor is only cooled as anticipated after renovation.

Building 669 Drawings used in Energy Modelling by PPG

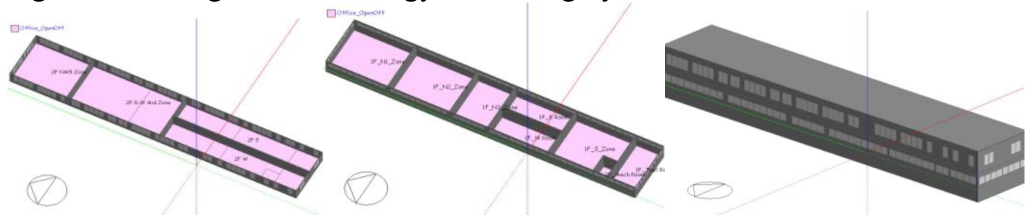
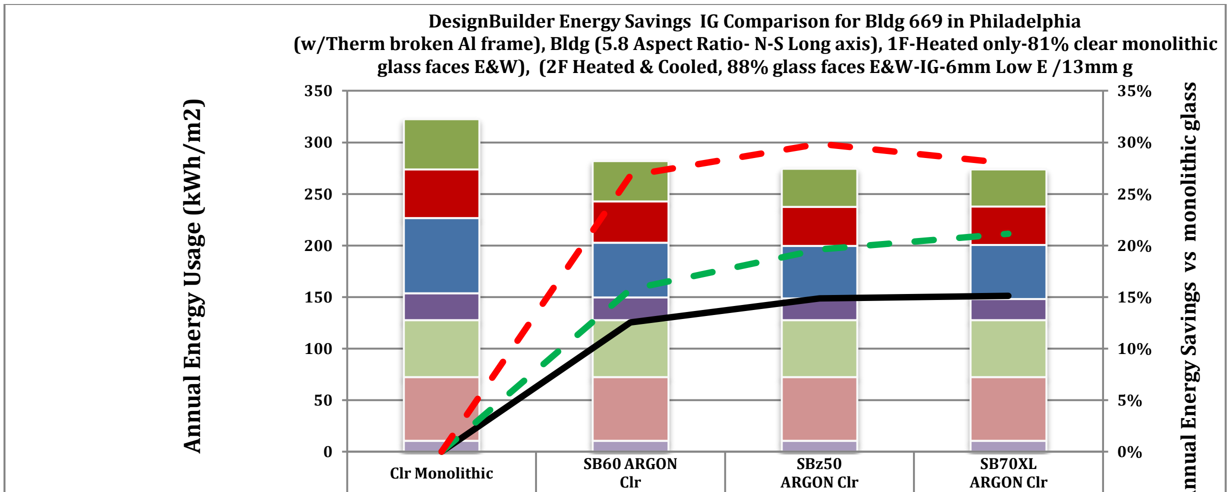


Figure 25 Building schematics from DesignBuilder simulation software for Building 669 in the Navy Yard.

The windows modeled in the 2F were IG's of Solarban® 60, Solarban® z50, and Solarban® 70XL compared with clear monolithic glass, clear-clear or Atlantica® (tint)-13mm argon gap-clear. The tint-clear IG was done to a baseline that meets the DOE minimum for glazing in climate zone 4. Building energy modeling is broken down into the following energy usages: fan, heating, cooling, pump, equipment, lighting, and DHW. Glass configurations affect the fan, heating, cooling and pump energies while in this model the others remain constant. Thus, this analysis demonstrates savings associated with glazing configuration only. The EUI data for Building 669 using different Low E glasses are shown in Figure 26 below and are compared to a clear monolithic glass. The best glazing for this building is Solarban 70XL glass.

The heating and cooling loads in buildings are affected through the glazing by reflection, transmission or absorption of solar energy. Low emissivity coatings on glass help reflect heat away from the glazing (externally to prevent heat from entering in the summer or internally to keep heat from leaving in the winter). With respect to glazing, the optimization of keeping heat "in" or "out" and daylight "in" is affected by regional climate so that some glazing products are better in a heating dominated climate (low U_{value}=good insulation is more important) while other glazing products are better in a cooling dominated climate (low solar heat gain coefficient=high blocking of solar heat load is more important). However, mixed climates like Philadelphia are more complicated when choosing glazing because heating and cooling are both required in commercial buildings and often at the same time. The glazing choices used in this simulation are affected by climate such that the glazing offering the best heating savings is Solarban z50 while the glazing offering the best cooling savings is Solarban 70XL. Thus, it is important to have the actual building specifications in the simulation so that the model predicts the heating and cooling usage as accurately as possible so that the optimal glazing can be chosen based on building heating and cooling usage and the associated costs in the region. This model predicts that cooling is higher than heating usage which is dependent on the heating and cooling systems used in this model which were based on ASHRAE 90.1-2010. Further improvement can be made in this model by using HVAC systems that are closer to the actual RTU's that are expected to be utilized in the retrofit.



	Clr Monolithic	SB60 ARGON Clr	SBz50 ARGON Clr	SB70XL ARGON Clr
Fan	48.6	39.2	36.8	35.9
Cooling	47.3	39.9	38.0	37.3
Heating	72.7	53.2	51.0	52.4
Pump	26.1	21.9	20.9	20.5
Equipment	55.2	55.2	55.2	55.2
Lighting	61.8	61.8	61.8	61.8
DHW Generation	10.7	10.7	10.7	10.7
Total Annual Energy Savings	0	12.6%	14.9%	15.1%
Cooling Savings	0	15.7%	19.6%	21.2%
Heating Savings	0	26.8%	29.9%	28.0%

Figure 26 Building Energy Simulation using DesignBuilder and EnergyPlus for Building 669 in Philadelphia for high performance glazing versus clear monolithic glass.

In this model, the energy savings associated with HPGT is less than the actual savings because the building baseline materials used in this model were that of the renovated building and not of the existing building which are dated. When comparing the savings with different glazing baselines like clear-clear and tint-clear IG units the savings are further reduced because the baseline glazing is better performing while the building baseline parameters are those of the renovated building which is better than the existing building. This was done because the retrofit will require the building be brought up to code, regardless of the glazing selected. Thus, the comparison is not clearly showing the energy savings achieved solely from high performance glazing.

When the baseline case is clear monolithic glass, Solarban 70XL glass is the top performer and offers a total building energy savings of 15% and a cooling savings of 21%; when the baseline is a clear-argon-clear unit the total savings drops to 6.4% and 9%, respectively, as shown in Table 4. A summary of the benefits of HPGT on heating and cooling energy savings is shown below as compared to different baseline glazing configurations demonstrating the energy savings opportunities of glass in a small 2F building renovation when only half of the glazing is expected to be replaced and 88% of the windows face east and west which requires more energy consumption. For this renovation, choosing the highest performance glazing minimizes the effect of the existing E-W building orientation. These savings can be further enhanced with lighting and shading integrated technologies.

Table 4 Summary of the energy saving benefits of HPG versus three different baseline glazings.

	Solarban 60 Glass	Solarban z50 Glass	Solarban 70XL Glass
	Low E/Argon/ Clear IG vs existing Clear MONOLITHIC		
Total Energy Savings	12.6%	14.9%	15.1%
Cooling Savings	15.7%	19.6%	21.2%
Heating Savings	26.8%	29.9%	28.0%
	Low E/Argon/Clear IG vs Clear/Argon/Clear IG		
	Solarban 60 Glass	Solarban z50 Glass	Solarban 70XL Glass
Total Energy Savings	7.3%	9.8%	10.0%
Cooling Savings	12.3%	16.3%	17.9%
Heating Savings	11.0%	14.8%	12.5%
	Low E/Argon/Clear IG vs TINT/Argon/Clear IG		
	Solarban 60 Glass	Solarban z50 Glass	Solarban 70XL Glass
Total Energy Savings	3.6%	6.2%	6.4%
Cooling Savings	2.9%	7.3%	9.1%
Heating Savings	11.8%	15.5%	13.2%

In conclusion, the energy simulation work using high performance glazing technology in the “simulation building” provided region-specific data showing the energy efficiency performance benefits of glazing in advanced energy retrofit projects. This work will continue in BP3, with continued simulation work on Building 669 and additional simulation and demonstration activities of high performance glazing installed in Purdue’s test facility.

8. Roof Retrofit Technologies

Three major roof components were demonstrated through simulation in BP2:

- Increased roof Insulation
- Improved Roof Membrane System
- Skylight & Glazing System

These subsystems were selected based on analysis showing that they have the largest impact on increased efficiency while affecting the largest number of buildings in the region. The demonstration simulation was done for multiple sites as described below. Demonstration of the recommended roof components in buildings with measurement and verification equipment is expected to occur at the chosen sites in BP3.

Demonstration Site #1: Building 669 – Naval yard, Philadelphia
Demonstrated Increased Roof Insulation & Improved Roof Membrane System

Background

Roof replacement technologies including increased roof insulation and improved roof membrane systems were evaluated through simulation supporting the retrofit of Building 669, a 20,425 gross square foot two story building constructed in the 1942/1943 timeframe. The building is owned by PIDC as a service facility for Dry Dock #2. PIDC desires to retain ownership of the dry-dock facility including Building 669 as a critical asset for the ship services part of the Navy Yard. (Figure 27) Rhoads Industries currently leases Building 669, Dry-dock #2 and the Pump House for its Maritime business unit. Rhoads Industries holds a lease with 11.5 years remaining and has two ten year options for renewal.

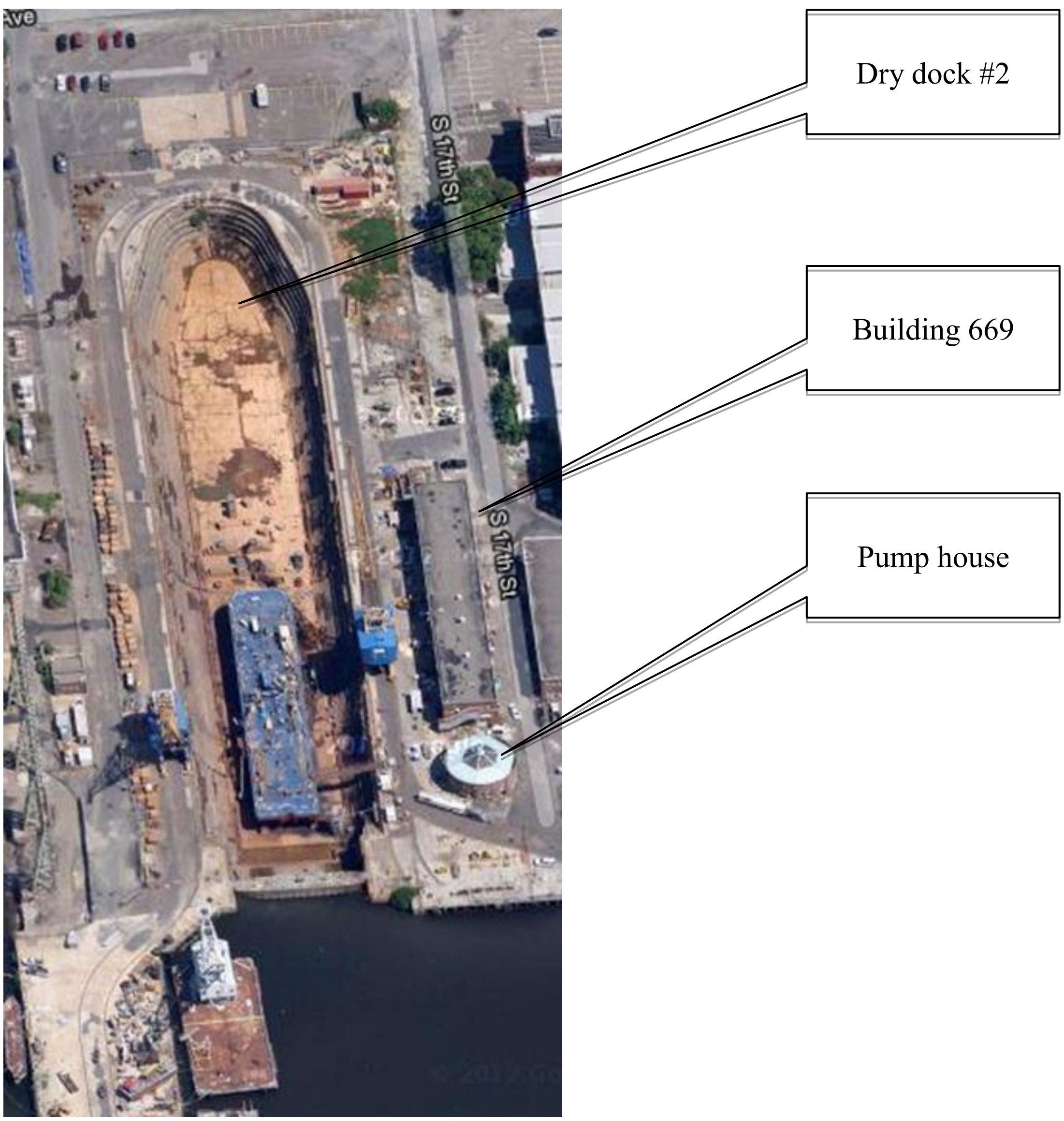


Figure 27 Dry Dock #2, Building 669 & Pump House

The roof was determined to be in very poor condition (Figure 28), which will require a complete tear-off of the existing built-up roof qualifying it as a deep retrofit. Complete removal of the roof demands that the new insulation levels meet existing codes followed in the region which are ASHRAE 2007/IECC 2009 that require a minimum insulation level of R-20 for the Philadelphia region.

Figure 28 Roof of Building 669

An investigatory meeting with Rhoads Industries management unveiled that they were thinking of potentially putting a PV solar system on top of the roof at a later date. So, they asked the HUB team to include a white roof system that would support a future PV installation into the list of possible roof scenarios. The roof deck beneath the existing built-up roofing was observed to be cement deck, so special precautions would have to be taken should a white roof be chosen.

Process

Based on HUB research and input from the building tenant, various options were investigated for the roofing membrane. Two black membrane systems were chosen as the best HUB recommendations and two white systems were chosen to support the tenant request of PV ready options. These include:

- White Built-up roof (3/4" thick multiple plies)
- 90 mil thick SureSeal Black EPDM
- 145 mil thick Sure White EPDM
- 80 mil thick Sure Flex PVC membrane

Should one of the HUB recommended black membranes be chosen, the layers for the roof system over the cement deck would be:

- 4" thick Polyiso rigid board insulation laid in two layers with staggered joints
- ½" thick cover board

Should a white PV solar ready roof option be chosen, additional materials would need to be added to the design to eliminate condensation issues and support the weight of solar panels. In order to overcome the issue of condensation, increased insulation with efficient installation techniques were recommended. The recommendation included providing an insulation of R-24 laid in two layers with staggered joints. The layers were recommended to be fully adhered, thus avoiding mechanical fasteners. This strategy helps prevent the seepage of moisture through either fastener penetrations or the insulation joints. The staggering of joints also prevents thermal bridging, thus providing a better thermal value to the entire roof system. It would also require a vapor retarder layer to eliminate condensation issues associated with the cement deck. Also, PVC membranes have higher seam strength compared to EPDM membrane and permit thin film PV to be directly adhered to the membrane. The white PV ready roof system would also require a recommended DensDeck rigid cover board which proves to be more effective against deterioration or warping compared to other cover board options when the additional weight of the panels was added. A white paper explaining these characteristics for a PV ready roof was submitted to the client.

The above mentioned roofing membrane recommendations were simulated in TRNSYS software and the options were then narrowed down to two "best case" recommendations based on:

- Annual Load Reduction
- Reduction in Energy Costs
- Initial Material Costs

The two recommendations were:

1. 90 mil thick fully adhered SureSeal EPDM membrane
2. 80 mil thick fully adhered SureFlex PVC membrane

Although the membranes are two different colors, the simulations indicated similar results for both in energy consumption due to efficient insulation levels negating color of membrane.

The energy savings achieved through increased roof insulation over the existing baseline was simulated to be around 20.90% (Figure 29)

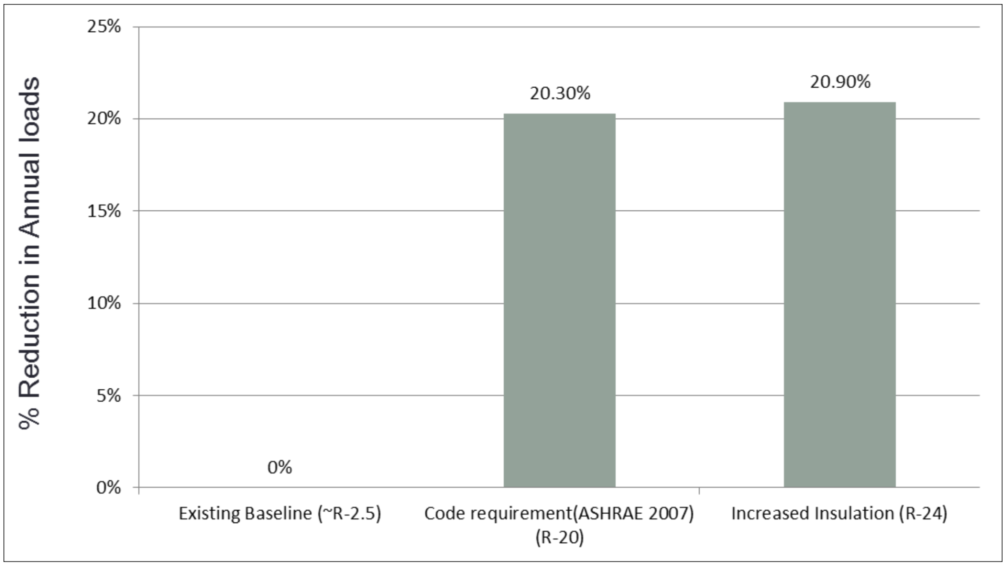


Figure29: Roof Insulation and its impacts on the annual loads

The requirement for PV ready roof along with efficient installation techniques for various components within the roofing system resulted in an increased labor and material cost compared to a traditional roof retrofit. The HUB team generated an installed cost of $75,000.00 for the roof retrofit based on market and manufacturer intelligence. The cost from a certified contractor to install the 90 mil Black EPDM HUB recommended system was $129,865. The installed cost of the PV ready system was $152,000, or roughly 15% higher than the HUB recommendation. Upon further discussion with the roofing contractor, it was decided that a 60mil Black EPDM membrane would be sufficient for energy efficiency while significantly lowering the cost. This change did not affect the simulation results and % energy savings. The installed cost for the 60mil Black EPDM is $111,868. Therefore, the 60 mil Black EPDM became the final recommendation from the HUB team, which was roughly 33% higher than the initial estimation. The difference was thought to be due to the cost of working in the Naval Yard and contractor variability. The team is now awaiting the client’s decision on which option they would like to move forward with.

Based on the cost and energy savings identified through the TRNSYS simulation models, payback period was calculated to be ≈13%for roof retrofit options. The payback period for roof retrofit only was found to be a little higher than the target 8%, but was similar to the payback period of just changing the glazing which was ≈14%. The overall payback calculated after incorporating roof into the other retrofit strategies for envelope, glazing and HVAC systems was found to be:

1. For EPDM membrane roofing: 5.5 years
2. For PVC membrane roofing: 5.7 years

These statistics help to identify the importance of an integrated systems approach. The integration of all the systems within the building helps to achieve better energy savings resulting in a reduced payback period in comparison to performing an individual component retrofit.

Results

Thus, the recommended roof retrofit strategy for Building 669 helped to achieve ~20% reduction in annual loads for Building 669. When all the retrofit strategies (such as envelope, glazing, HVAC) were simulated as an integrated approach along with the roof retrofit, the overall reduction in energy consumption achieved was 60%.

Demonstration Site #2: Building 661 – Naval Yard, Philadelphia

Demonstrated Increased Roof Insulation

Beginning in BP1 and continued in BP2, simulations were performed to identify the impact of increased insulation in a roof for Building 661 using Energy Plus in collaboration with Task 4.4. Six alternative roof insulation measures (including the benchmark model) were investigated. They had varying thermal insulation levels starting from R-5 (benchmark) up to R-90 (super insulation) including R-14.7 (ASHRAE 90.1 compliant), R-30, R-40 and R-70 insulation cases. The Building 661case has two different roof configurations as given below (for gym section on the west side, and front office section on the east side). Increasing thicknesses of roof thermal insulation are applied as two distinct layers assumed to be applied above and below of precast concrete structure existing for both roof configurations.

ROOF ASSEMBLY of Building 661 GYM SECTION

R-5 (Existing):

- Single ply EPDM Roof membrane (1/2”)
- PUR Foam Board (1”)
- Precast Concrete (4”)

Other Roof Alternatives:

- Single ply EPDM Roof Membrane (1/2”)
- Insulation Layer 2
- Precast Concrete (4”)
- Insulation Layer 1
- Gypsum Board (1/2”)

ROOF ASSEMBLY of Building 661 FRONT OFFICE SECTION

R-5 (Existing):

- Roof Slate Tiles (1/2”)
- Nailing concrete (2”)
- Precast Concrete (3/2”)
- Fiberboard Ceiling (1/2”)

Other Roof Alternatives:

- Roof Slate Tiles (1/2”)
- Nailing Concrete (2”)
- Insulation Layer 2
- Precast Concrete (3/2”)
- Insulation Layer 1
- Gypsum Board (1/2”)

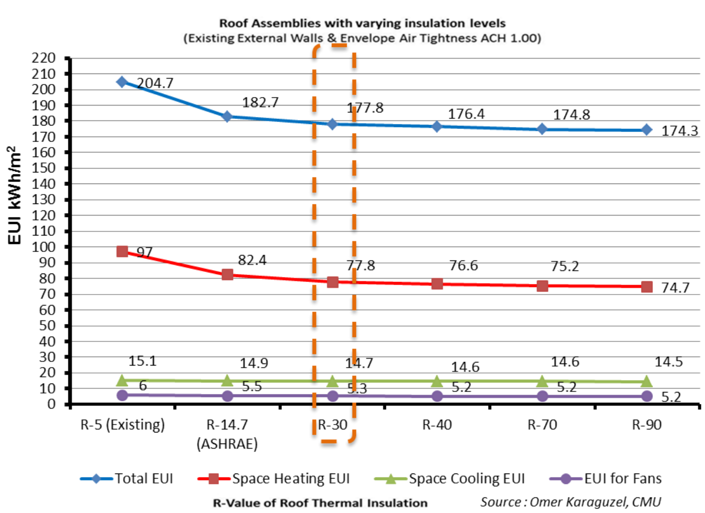
A summary of parametric studies done by Subtask 4.4 is provided in Table 5. The table includes roof insulation R-values of different alternatives, entire roof R-value, entire roof U-factor in SI units, insulation thicknesses for the two separate layers, and total roof thickness together with percent deviation from the benchmark thickness. The table also includes simulation results for heating, cooling, fan and total building energy.

Roof Insulation R-value IP [ft^2 °F h/Btu]	**Entire Roof R-value IP** [ft^2 °F h/Btu]	**Entire Roof U-factor SI** [W/m^{2}K]	**Insulation Layer 1 Thickness** [Inch/cm]	**Insulation Layer 2 Thickness** [Inch/cm]	**Total Roof Thickness** [Inch/cm]	**Percent Change in Roof Thickness** [%]	**Annual Energy Use Intensity – EUI (Heating/Cooling/Fans/Building Total)** *[kWh/m2] [kBtu/ft^2]*	**Percent Change in Annual EUI (Heating/Cooling/Fans/Building Total** **[%]**
R-90	R-93	0.061	6”/15.24	7”/17.78	18”/45.72	227%	H: 74.7 C: 14.5 F: 5.2 ∑: 174.3 H: 23.6 C: 4.6 F: 1.6 ∑: 55.2	H:-23% C: -3.8% F: -13.8% ∑: -14.8%
R-70	R-71.8	0.079	4”/10.16	6”/15.24	15”/38.1	172%	H: 75.2 C: 14.6 F: 5.2 ∑: 174.8 H: 23.8 C: 4.6 F: 1.6 ∑: 55.4	H: -22.5% C: -3.6% F: -13.5% ∑: -14.6%
R-40	R-44.3	0.128	3”/7.62	3”/7.62	11”/27.94	100%	H: 76.6 C: 14.6 F: 5.2 ∑: 176.4 H: 24.2 C: 4.6 F: 1.6 ∑: 55.9	H: -21.0% C: -3.6% F: -12.5% ∑: -13.8%
R-30	R-33.8	0.168	3”/7.62	1.5”/3.81	9.5”/24.13	72%	H: 77.8 C: 14.7 F: 5.3 ∑: 177.8 H: 24.6 C: 4.6 F: 1.6 ∑: 56.3	H: -19.8% C: -2.6% F: -11.6% ∑:-13.1 %
R-14.7 (ASHRAE)	R-17	0.334	3”/7.62	2”/5.08	10”/25.4	81%	H: 82.4 C: 14.9 F: 5.5 ∑: 182.7 H: 26.1 C: 4.7 F: 1.7 ∑: 57.9	H: -15.1% C: -1.6% F: -8.6% ∑: -10.7 %
R-5 (EXISTING)	R-7	0.814	-	1”/2.54	5.5”13.97	0%	H: 97.0 C: 15.1 F: 6.0 ∑: 204.7 H: 30.7 C: 4.8 F: 1.9 ∑: 62.8	H: 0.0% C: 0.0% F: 0.0% ∑: 0.0%

Table 5: Roof thermal insulation value comparisons

Results

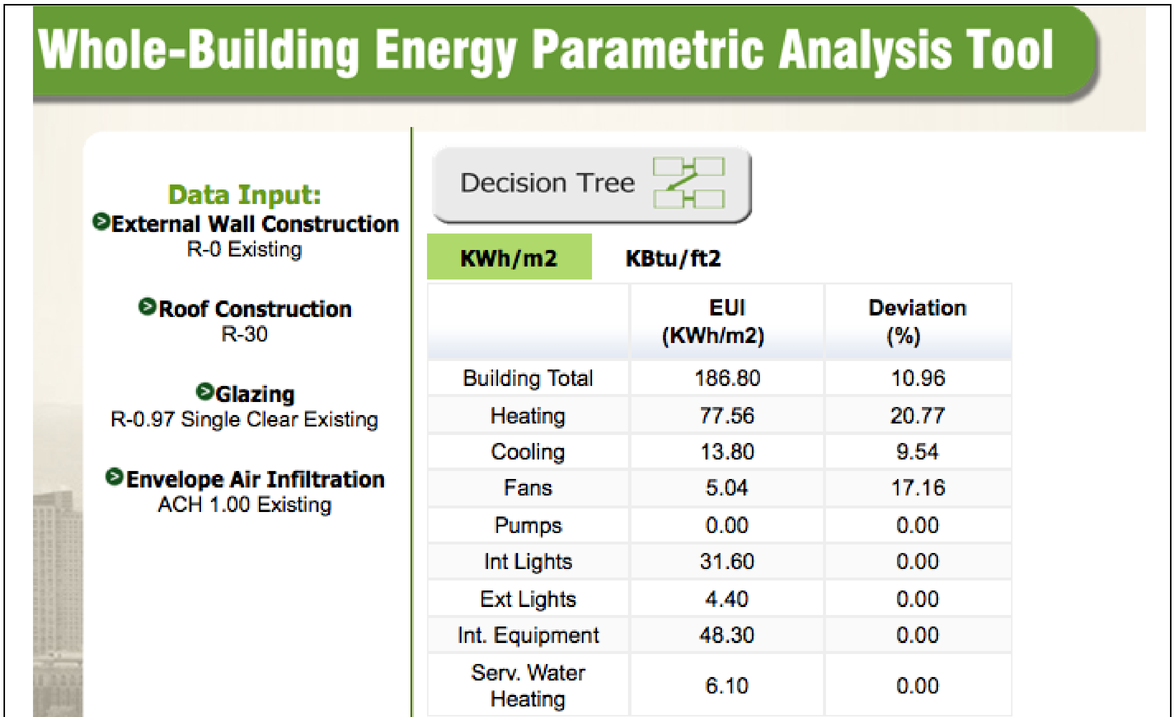
The results obtained from these simulations indicated ≈15% improvement in EUI for the building when the roof insulation was increased from an existing R-5 to R-90. However, the simulations also indicated a diminishing rate of return that occurs with R values higher than R-30. Therefore, the increase from R-30 to R-90 provides minimal energy reduction improvement while demanding a large increase in insulation thickness as well as increase in cost for added insulation layers. Based on these findings, the HUB recommendation is to increase insulation to an R-30 roof which provides ≈13% improvement in the overall EUI. Figure 30 below indicates the impact of various insulation levels on the overall EUI for Building 661 as well as the corresponding increase in roof thickness for each insulation value.



R-value of Roof Insulation	% change in Roof Thickness
R-5 (Existing)	0
R-14.7 (ASHRAE)	81%
R-30	72%
R-40	100%
R-70	172%
R-90	227%

Figure 30: Effect of Roof Insulation on the overall EUI

Based on simulation results of Building 661, increasing the roof insulation from the existing condition to R-30 can reduce the total heating, cooling, and fan Energy Use Intensity (EUI) by 13% (Figure 31).



	EUI (KWh/m2)	Deviation (%)
Building Total	186.80	10.96
Heating	77.56	20.77
Cooling	13.80	9.54
Fans	5.04	17.16
Pumps	0.00	0.00
Int Lights	31.60	0.00
Ext Lights	4.40	0.00
Int. Equipment	48.30	0.00
Serv. Water Heating	6.10	0.00

Figure 31: Benefits of R-30 insulation with Energy breakdowns

Demonstrated Skylight and Façade Glazing Specifications

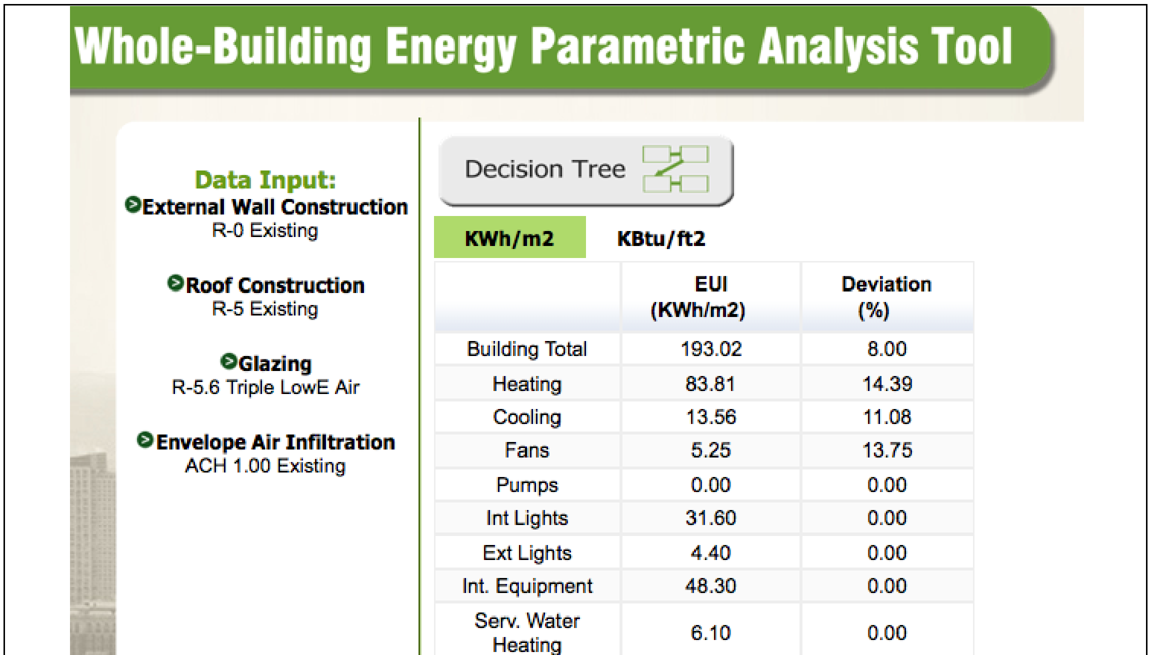
Demonstration of facade and skylight glazing through simulation of Building 661 in Philadelphia, PA. The skylights in building 661 occupy a large area of the roof and are not the traditional inserted skylight. Their skylights are part of the roof structure.

The same type of glazing for the façade glazing and the roof skylight glazing was assumed. When changes were made to the façade, the same changes were assumed for the roof skylight. The effects of various glazing types with different thermal resistance and solar and visible transmittance were analyzed in collaboration with Task 2. Ten (10) glazing alternatives were considered and key properties are listed in the Table 6, however 6 out 10 alternatives are incorporated into the simulation models and analyzed in detail. These types are single clear glazing (reflecting the existing case – benchmark model), double and triple alternatives with low-E coating and filled with either air or argon gas and a super-insulated case which is a quadruple glazing with krypton mid-pane gas type. All glass panes are 6mm thickness (except single clear type – 3mm) and mid-pane gas has a thickness of 13mm. No change was applied to window frames which are assumed as 400mm wooden for existing case and 400mm UPVC for other alternatives. Glazing options are applied evenly to all window surfaces facing all orientations as well as to skylight components.

Window Alternative	Assembly Explanation	U-factor (W/m^2K)	R-Value (hft^2 $^oF/Btu$)	SHGC	Visible Transmittance	Frame Type	Frame U-factor (W/m^2K)
Single Glazing	3mm clear glazing	5.89	0.97	0.86	0.89	4cm wooden	3.633
Double Glazing (Air) – low-E	6/13/6mm low-E with air gas	1.91	2.9	0.59	0.74	4cm UPVC	3.476
Double Glazing (Air) - clear	6/13/6mm clear with air gas	2.66	2.1	0.70	0.78		
Double Glazing (Argon) – low-E	6/13/6mm low-E with argon gas	1.81	3.1	0.59	0.74		
Double Glazing (Argon) – clear	6/13/6mm clear with argon gas	2.51	2.3	0.70	0.78		
Triple Glazing (Air) – low-E	6/13/6/12/6mm low-E with air gas	1.01	5.6	0.46	0.63		
Triple Glazing (Air) - clear	6/13/6/12/6mm clear with air gas	1.72	3.3	0.61	0.69		
Triple Glazing (Argon) – low-E	6/13/6/12/6mm low-E with argon gas	0.87	6.5	0.46	0.63		
Triple Glazing (Argon) – clear	6/13/6/12/6mm clear with argon gas	1.59	3.5	0.61	0.69		
Quadruple Glazing (Krypton)	5.7mm clear glass + 9.7mm krypton + Heat Mirror suspended film 1 + 9.7mm krypton + HM Suspended film 2 + 9.7mm krypton + 5.7 mm clear glass	0.47	12.19	0.20	0.478	4cm UPVC	3.476

Table 6*:* Comparison of glazing alternatives

Results: Based on simulation results of Building 661 in Philadelphia, PA conducted by CMU, replacing the facade and skylight glazing from the existing conditions with double glazing or triple glazing with an air fill can reduce the total heating, cooling, and fan Energy Use Intensity (EUI) by 9.3% and 13.2% respectively (Figure 32).



	EUI (KWh/m2)	Deviation (%)
Building Total	193.02	8.00
Heating	83.81	14.39
Cooling	13.56	11.08
Fans	5.25	13.75
Pumps	0.00	0.00
Int Lights	31.60	0.00
Ext Lights	4.40	0.00
Int. Equipment	48.30	0.00
Serv. Water Heating	6.10	0.00

Figure 32: Benefits of Triple Glazing with Energy breakdowns

Based on the simulation results, the optimum benefit occurs at double glazed windows. Triple and quadruple glazed windows have a diminishing rate of return compared with the change from single to double glazed windows, however triple glazed windows with an argon fill provide the best heating EUI improvement (Figure 33). The super glazing case of quadruple with krypton gas type results in a slight increase with respect to triple glazing with argon option due to reduced SHGC. Such an effect is at the opposite for cooling energy consumption. There exist marginal variations in fan energy by changing glazing types.

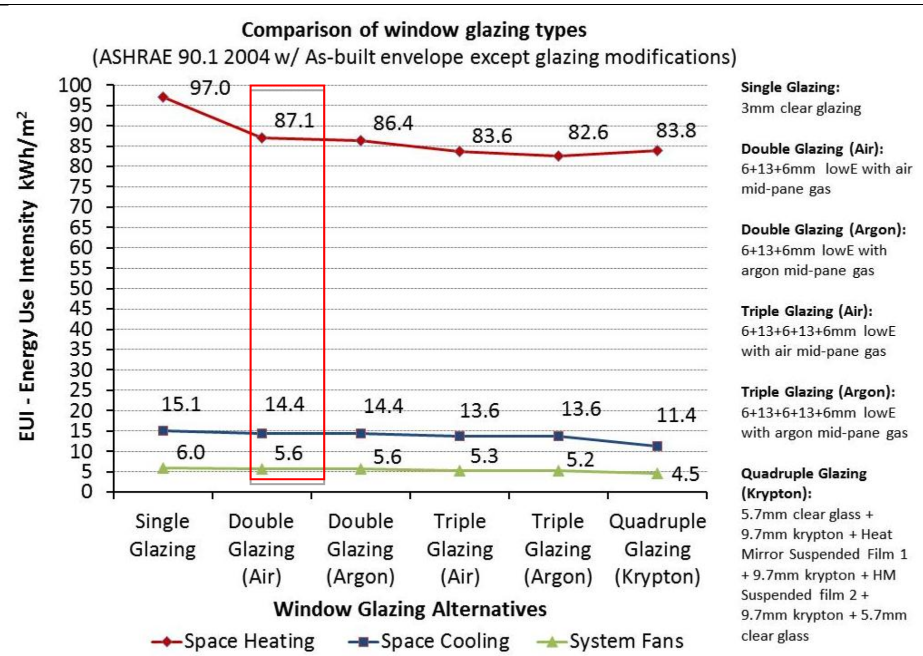


Figure 33: Comparisons of glazing types

Demonstration Site #3 – Burns & Scalo Building Pittsburgh, PA

Demonstrated Color and Type of Roof Membrane

The roof membrane color or type of roof surface affects the heat absorption and heat reflectance properties of the roof. A conventional dark roof absorbs most of the heat incident on the roof surface resulting in an increased temperature differential between the roof surface temperature and the ambient air temperature. This heat is then transmitted into the building, thus, increasing the building cooling loads. A cool roof on the other hand reflects off most of the heat, reducing the temperature differential between its surface temperature and the ambient air temperature which reduces the impact on the building cooling loads. The surface temperature of cool roofs can be 40ºC lower compared with a traditional black roof. Cool roofs can reduce energy loads by ±15% and has a $3 million potential energy savings for Philadelphia, PA. Appropriate membrane layering can reduce condensation problems caused by the cooler roof temperature, reduce the temperature of the roof and provide energy savings.

To identify the benefits of high performance roof membranes, CMU collaborated with Burns & Scalo (Roofing, Contracting, and Real Estate Company) in a full scale test building facility where multiple roof membranes (black, black with shade, white, sedum, and moss) were compared. Temperature sensors were installed at three levels: 6" above the roof, on the roof surface, and in the ceiling (conditioned side of the roof). To identify additional benefits such as heat transfer, CMU prepared linear regression and building simulation models of the test facility. Regression and simulation results were compared with the measured temperature and energy consumption data to verify findings.

Results

Annual temperature results:

Based on 12 months of measured data, it was observed that black roof temperatures fluctuated greater than white roofs. The white membrane reduced the fluctuation of the membrane surface temperature by 30-40%. This increase in temperature fluctuation may impact the life expectancy of the roof and the building's heating and cooling energy. In addition to temperature fluctuations, white roof temperatures were generally cooler than black roofs. White roofs were 6 to 18°C cooler compared to the conventional black roof when ambient temperatures were higher than 22°C (72°F). In the 0-22°C ambient temperature range, the difference between the roof types was small (0-3°C on average). When temperatures were below -10°C, both white and black roofs behaved similarly. While the exterior temperature fluctuated, inside temperatures in the conditioned spaces had only small deviations from each other.

Partial Cooling Season Temperature Results:

During warmer months, the temperature difference between the black and white roofs was greater than the annual average. During July 2012-October 2012, the shaded white and black roofs significantly reduced the membrane temperature diurnal swings compared to the black unobstructed membrane. The white unshaded roof reduced the maximum and minimum range 20-30% while the black shaded and white shaded roofs achieved a 40-50% and 50-60% reduction respectively compared to the black unshaded roof.

Heat Transfer Results:
In the winter, the white roof had 12% more heat loss (due to colder membrane temperatures) than black roofs and 25% more than green roofs. Depending on internal thermostat set points, this heat loss may need to be supplemented by additional mechanical heating. In terms of heat gain, the black roof allowed 66% and 84% more heat to flow into the space than the white and green roofs respectively. In the summer months, the black roof had a positive net heat flux while the white and green roofs had a negative net heat flux. The black roof allowed 57% more heat to enter the building than the white roof and 85% more than the green roof. Across the year, the black roof had over 58% and 87% more heat entering the building compared to white and green roofs respectively. Adding the absolute value of heat gained and lost across the year, black roofs allowed 15% and 47% more heat to flow through the roof assembly (i.e.in or out) compared to the white and green-moss roofs respectively. Both white and green roofs had more sizable reductions of heat gain from the reference black roof than differences in heat loss.

Based on simulation results, the heat loss and gain measurements equates to a cooling energy savings, but a heating energy penalty. In Pittsburgh, the white roof requires 16 kBTU/m^2/yr more in site natural gas than the black roof to replace the annual net heat lost. The net energy benefit for each roof type was determined by adding the energy (using average Pittsburgh electricity and Natural gas costs), material and installation costs (in Pittsburgh, the white roofs cost \$0.01/m^2/yr more than black roofs), and savings together. Based on these findings there is only a small financial benefit between black and white roofs. Simulation results for warmer cities indicate a larger financial benefit in warmer climates.

Other Technologies Investigated:

Top-lighting Strategy:
Roof retrofit offers an ideal opportunity to incorporate top-lighting strategy within the roofing system. This helps to achieve reduced energy consumption by reducing the lighting energy loads within a building. Analysis helped to identify that top-lighting strategies provide 30% more light per unit area of glazing compared to side-lighting and also a more uniform distribution of illumination. These strategies are effective for buildings which have deep plan configuration where the side-lighting is effective only for the perimeter lighting but not for the core spaces.

Research and analysis related to various top-lighting strategies helped to identify that skylights provide various qualitative as well as quantitative benefits, such as:

Energy savings:

> Skylights help to reduce the electric energy consumption by reducing the dependence on artificial lighting. This also relates to cost savings. Various case studies have revealed approximately 40% to 75% savings in lighting energy with the use of skylights integrated with efficient lighting control strategies.

Increase in Sales for Retail Stores:

> Natural light made available through skylights produces a high color rendering effect which enhances the visual aspect of the products on display. This has found to positively impact sales in retail store. A case study done by Heschong Mahone Group (HMG) for a retail chain indicated that the addition of sky-lights within a store led to an increase in sales from \$2/sq.ft to \$2.61-\$2.98/sq.ft which translates to ~40% increase in sales.

Improved Productivity for Offices:

Availability of natural light is also found to impact the productivity of employees in office buildings. A case study of the Lockheed Martin Sunnyvale, CA indicates a 15% increase in productivity through incorporation of skylights within the office space.

Use of skylights impacts not only the lighting energy but also the heating and cooling energy within a space. The amount of glazing in a skylight system accounts for heat losses and gains. As the skylight aperture size decreases, the overall building energy consumption also decreases up to a certain point due to reduction in heat losses or heat gains. Thus, the overall benefits reaped from a skylight system depend on the optimum size of the aperture.

A simulation study done by Heschong Mahone Group (HMG) for a grocery store in Albany, New York, identifies this threshold point at 5% of the floor area under the roof (Figure 34). Thus, maximum energy savings as well as cost savings can be achieved at 5% Skylight to Floor area ratio (SFR). Also, codes such as ASHRAE Standard 90.1, 2010 limit the maximum SFR to 5% for climate zones 4 and 5.

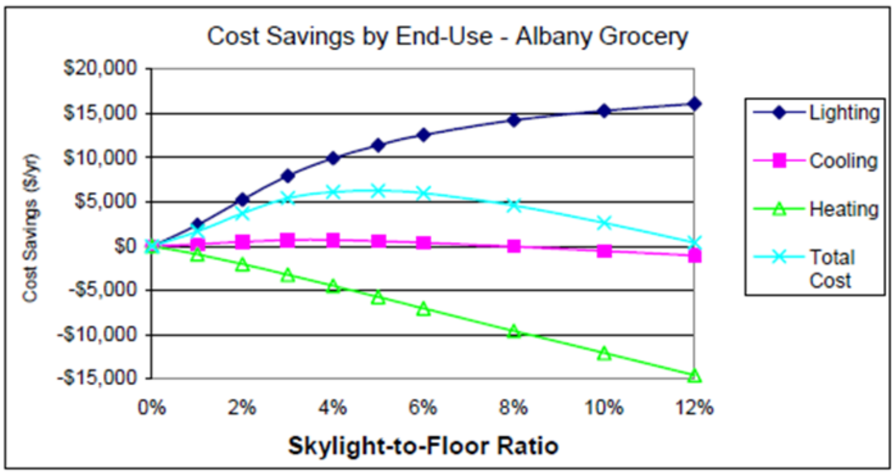


Figure 34: Impact of skylight aperture size on cost savings

Another important component of a skylight system that affects the heating and cooling loads is the skylight glazing. The team analyzed the four major characteristics of the glazing material that affect the energy savings achieved from a skylight and also identified the threshold for each property in order for the system to qualify for an Energy Star skylight. These are:

- Visible transmittance: Minimum visible transmittance required = 70%
- Haze value: The glazing material or diffusers used in conjunction with the glazing should have at least 90% haze value.
- Solar heat Gain Coefficient: ASHRAE standards 90.1, 2010 require the SHGC to be lower than 0.39
- U factor: To be less than 0.55 Btu/h.sq.ft.^{o}F

A simulation study was conducted for an office building specific to Philadelphia region. The skylight system simulated was a double glazed skylight with a traditional metal frame. The results of the simulation study were (Table 7):

Space Loads	Savings for Philadelphia
Lighting Energy	75%
Heating Energy	-47%
Cooling Energy	3%
Total Energy	**20%**

Table 7: Energy savings achieved with the help of skylights (Moeck et al.)

These results indicated 47% heat loss although the lighting energy savings achieved were 75%. Further analysis and research was conducted in order to identify developed technologies that would provide better thermal efficiency compared to traditional skylights.

One such technology identified and analyzed is the RIM technology with SIP curb components. The RIM (Reaction Injection Molding) technology encapsulates the glazing into a pigmented UV-stabilized, polyurethane retainer frame and ensures both unit size consistency and a weather-proof bond between both the materials. This technology eliminates the need for tapes, gaskets and sealants, reducing leakage typically associated with skylight systems. The polyurethane frame requires no maintenance and is also non-conductive, providing a thermal efficiency which is 38% greater than that of a metal–framed skylight.

The SIP curb components provide a higher thermal resistance with an R-value of 14.5 compared to an R-value of 5 for traditional metal frames (Figure 35). It is easy to install and less labor intensive. Also, these panels are 25% lighter in weight compared to metal curb components.

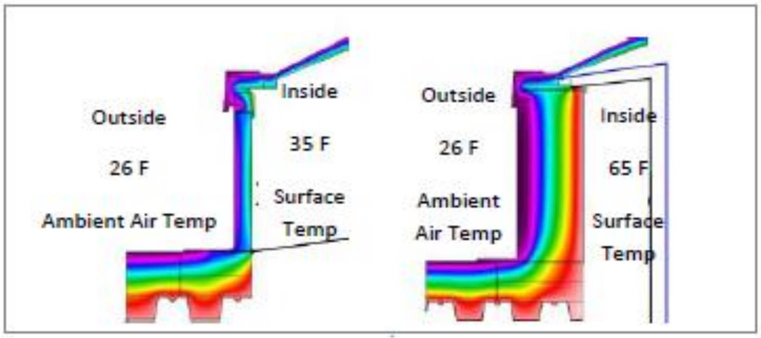


Figure 35: Thermal analysis of metal curb v/s SIP curb

Another technology identified and researched for top-lighting strategies is the incorporation of light tubes within roof retrofit. Light tubes are highly engineered products which are compact in size compared to a traditional skylight. These offer omni-directional illumination. The compact size ensures reduced glazing area which results in virtually no heat gains or losses. These are easier to install in retrofit applications compared to a traditional unit skylight and can also transmit light to lower floors within a building.

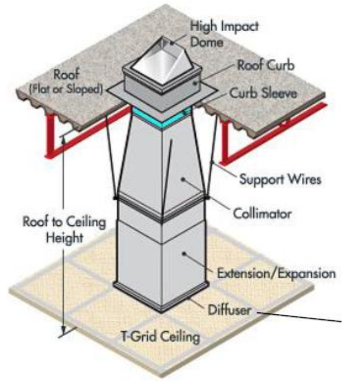


Figure 36: Components of a light tube

A light tube consists of the following components (Figure 36):

- Integrated reflectors to enhance light capture
- Fresnel lens with other enhancements which redirect low angle light into the building and at the same time reflect off excess heat.
- Highly reflective (claims of up to 99.7% reflectivity) factory-manufactured light wells
- Ceiling-level diffusers to reduce glare and hot spots
- Integrated shutters to control light output

Thus, light tubes are often available as an integrated system. These are provided with seamless flashing that provides a water-tight system. It is also equipped with various accessories such as daylight dimmer system for controlling the amount of illumination obtained within the space, diffusers at ceiling level to avoid glare and hotspots, additional electric kit which can supplement available natural light when the required illumination cannot be met with reliance on natural light.

<u>Market Availability:</u>

Both these technologies, RIM encapsulated skylights and light tubes are currently available in the market under different product names by various manufacturers.

Carlisle Drylight:
This is a unit skylight system that uses the Rim technology and is manufactured in unit sizes to be mounted over the SIP curb components. The Drylight factory curbs incorporate Carlisle's seamless PVC/TPO flashing sleeves which ensure a water-tight system. Thus, Drylight, skylight system by Carlisle, is available as an integrated system. Carlisle offers a 20 years warranty for all the components of the system

Carlisle SunPath tubular daylighting device:
The SunPath tubular skylight is a light tube which consists of high-impact acrylic dome, highly reflective Miro-silver coating for the light well, seamless flashing along with other accessories such as daylight dimmer system, ceiling level diffusers. Carlisle offers a 10 years warranty for the total roof system with this technology.

Solatube Daylighting Systems:
The Solatube Daylighting System is a light tube system which makes use of advanced Raybender technology along with Fresnel lenses to capture maximum daylight and reflect off excess heat. Solatube offers a 10 year warranty for this system.

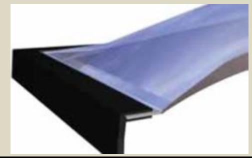
VTECH:
VTECH skylights are also curb mounted or self-flashing skylight system that make use of RIM technology.

The use of skylight system contributes to savings in lighting energy only when the system is effectively integrated with lighting control strategies. In-depth research and analysis of case studies indicated that the dimming strategy for lighting controls is the best suited option for the North-east Region with 50% cloudy conditions throughout the year. This strategy in lighting control provides maximum energy savings and also the best light quality with uniform illumination.

Various top-lighting strategies were, thus, analyzed during year 2 in terms of glazing properties, aperture opening and its impacts on lighting, heating and cooling loads, leakage as well as thermal issues. Economic analysis for these strategies helped to understand the overall energy and cost benefits along with approximate payback period for each. This economic analysis was based on market intelligence.

The payback period comparison chart below compares the initial cost of installation for a conventional double glazed skylight, a light tube and a RIM encapsulated skylight. Table 8 gives a comparison of saving achieved from each and the payback period associated with it.

Table 8 Summary of Skylight Options Considered

	Conventional Double Glazed unit Skylight	Light Tube	RIM encapsulated Skylight with SIP curb
			
Size of unit	5' x 6'	21"	4' x 4'
Area illuminated by each unit	702 sq.ft	517 sq.ft	625
Total Store Area to be illuminated	50,000 sq.ft	50,000 sq.ft	50,000 sq.ft
Number of units required	71	96	80
Cost per unit ($)	$1,500	$1,500	$1,800
Total installation cost ($)	$106,500	$144,000	$144,000
Energy Savings (%)	40% to 75%	48% to 75%	40% to 85%
Average annual cost of lighting energy	$1.22/sq.ft	$1.22/sq.ft	$1.22/sq.ft
Energy Savings ($/sq.ft)	$0.49 to $0.90	$0.58 to $0.90	$0.49 to $1.03
Total savings ($)	$24,500 to 45,000	$29,000 to $45,000	$24,500 to $51,500

The payback period associated with the three types of skylights is almost comparable. However, it is essential to understand that the Rim encapsulated skylight as well as light tubes provide certain non-quantifiable benefits over traditional metal framed skylights such as more thermally comfortable environment, reduced condensation as well as an integrated system.

Roof Retrofits – Guidebook

Selected roof demonstration findings and results were incorporated into a guidebook "Integrated Roofing Retrofits: High Performance Integrated Flat Roofs and Skylights" (Cochran, E; Loftness, V; Aziz, A; Mokashi, M; Kolosky, A: Hodari, S). The guidebook provides a summary of multiple integrated roof technologies that have the opportunity to save at least 20% of a building's energy while promoting a total building integrated retrofit. Roofs occupy a significant fraction of the built environment. Coffelt (2008) estimated that roofs occupy ≥25% of the total managed building area and according to Akbari et. Al. (2003) roofs occupy 20-25% of urban landscape in multiple U.S. cities. On a national scale, estimates for commercial building roofs for 2010 were approximately 2.6-8.2 billion square meters (28-88 billion square feet) of land area (Levinson & Akbari 2010; CEIR 2012; Chaudhari 2004) (Nagengast, A 2012). Roofs are replaced often and thus yield a platform for educating people on how to retrofit their roofs with new technologies such as high R value insulations, membranes, daylighting, and MEP technologies but also helping to reduce heat gain/loss through a large portion of the building. Roof retrofits can then act as a springboard to opening up a dialogue about whole building energy retrofits.

A guidebook of high performance roof technologies that can be implemented in building retrofit projects fills a remarkably large void in the energy and performance retrofitting education sector. Current manuals focus primarily on either owners or auditors/appraisers, and addresses either action planning or improvement of Lighting and HVAC equipment. With the goal of promoting total building integration, providing a document explaining methods of improving the performance of envelope features is vital to its success. The integrated roofing guidebook differs from existing roofing manuals due to its integrated roofing systems focus and the intended audience. It specifically addresses and conveys proper installation of retrofitting choices, "value added propositions," and the most ideal practices. This guidebook showcases multiple options and techniques to improving such things as heating, cooling, and fan loads, increasing daylighting in existing buildings, reducing lighting loads, selecting high performance membrane materials, and cost competitive integrated roof technologies. It is both an informative and "Best Practices" guide for contractors and building owners to drive them towards the most innovative retrofitting of buildings.

9. Photosensor Controlled Electric Lighting

Penn State investigated the performance of single-zone and multi-zone photosensor-based lighting control systems in spaces with windows (sidelighting) using computer models of the daylight and electric light distributions in spaces. A comparison of the potential energy savings of these systems showed that optimized multi-zone control utilizing smaller control zones can provide increased energy savings over a large single zone system. A multi-zone control system offers a more challenging calibration and layout condition, however, this study showed that a sequential multi-zone control system can greatly simplify both the control algorithm and system calibration, and deliver near optimum multi-zone performance.

Under a multi-zone daylight integrated lighting control system, the electric lighting in zones closest to a window are dimmed to a lower output condition than zones deeper into a space. This method is in contrast to single-zone control, where a larger, single group of luminaires is dimmed at once. In this research, in order to maximize the energy savings, the electric lighting within a control zone is dimmed to minimum output, then turned off to eliminate the power necessary for cathode heating, which can be as large as 14W for each two-lamp T8 dimming ballast. This is a significant energy saving feature in multi-zone control, since the lighting zone nearest the window can often be turned off.

To model the performance of multi-zone lighting control systems, computer software was written to determine the output level for each lighting control zone within a space that both minimizes power consumption and maintains a minimum target illuminance at each of the analysis points across a space. The ideal dimming levels under both single zone and multi-zone control were analyzed at all hours of the year for Perez sky distributions that were developed from the irradiance data provided in an Energy Plus weather file (.EPW file).

An example study space (32 ft x 28 ft x 10 ft) was considered that included four rows of luminaires running parallel to a North-facing exterior window wall (See Figure 37). This layout was studied with three rows of luminaires dimmed and the most interior row on at full output. The dimming levels and corresponding input power requirements for the controlled lighting zones were compared between an optimized three-zone approach and a single zone optimized system that dimmed all three rows together. At lower daylight levels when some dimming is required of at least one of the dimmed zones in the multi-zone system, the single zone system often consumed as much as 30-50% more power than the optimized multi-zone control system (see Figure 38). Daylight levels were sufficient at some hours that all three rows could be turned off, in which case both systems were operating at the same power level.

Dimming a single zone involves a relatively simple control system, whereas dimming three zones to different levels requires either three different photosensors, each linked to a daylight zone, or an algorithm that relates the output of each of the three rows to a single sensor. The latter is available in at least one manufacturer's commercial product. Applying a single photosensor avoids the potential for cross-talk between the electric light output of one zone and the input signal used to control an adjacent zone. Some manufacturers offer multi-zone control where each zone is controlled by a dedicated photosensor within that zone.

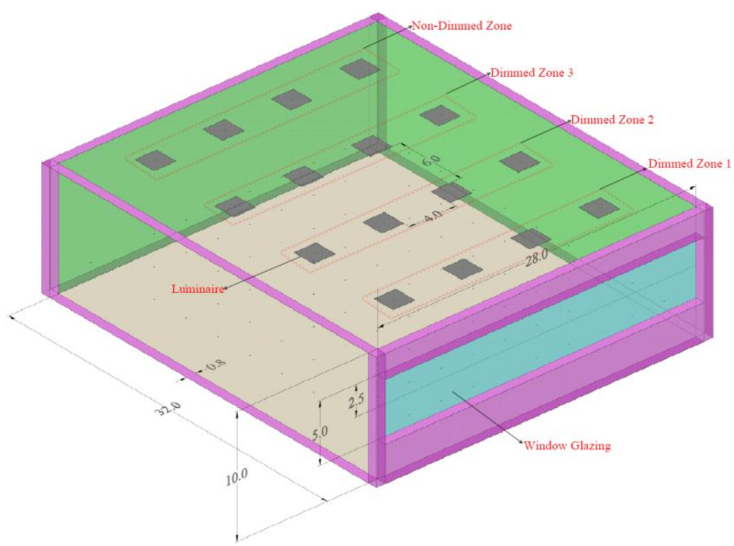


Figure 37. Test room for single zone and multi-zone lighting control of the three rows of lighting equipment nearest to the North-facing window.

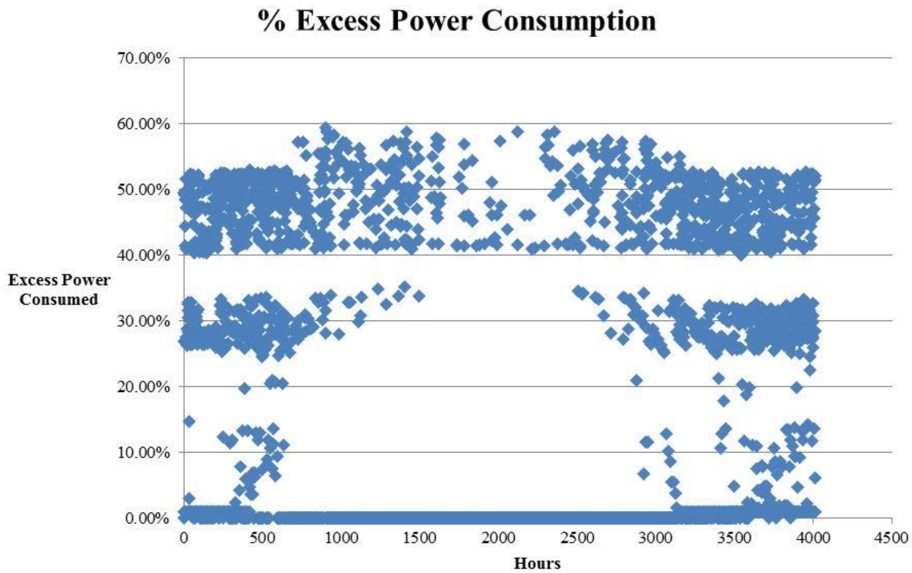


Figure 38. Excess power consumed by a single zone optimized lighting control system relative to a multi-zone lighting control system at each of the 4015 hours considered in this study (8AM – 6PM, daily).

In the space considered here, the single zone system was able to save 54.5% of the total space lighting energy required while the multi-zone system saved 13% more energy (for a total savings of 61.8%). It is important to note that these high levels of savings consider that electric lighting control zones can be turned off.

In reviewing the optimized multi-zone control algorithm performance, we observed that as daylight levels increased, the zone closest to the window would dim first, then as it reached near its minimum, the second zone would begin to dim. This operation, as shown in Figure 39, is very close to a sequential control algorithm where one zone is dimmed to off, followed by the next zone, and then finally the third zone. To test how such an optimized, fully sequential system would function, optimized control settings for this sequential dimming approach were computed across the analysis year. Sequential control provided nearly identical energy savings to the multi-zone control algorithm where each zone was set to a different dimming level that minimized energy consumption while maintaining work plane target illuminance at all points. The difference in energy savings was less than 1% between these two approaches.

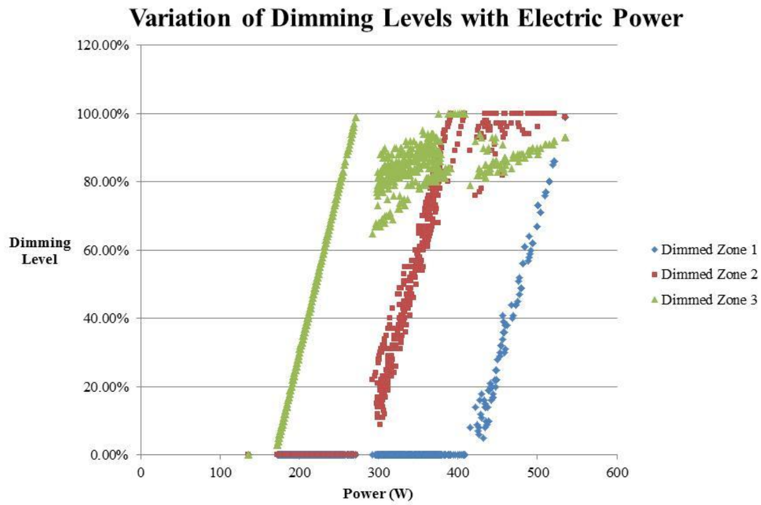


Figure 39. Dimming levels of the three lighting control zones under optimized multi-zone control. Note that these optimized control conditions are very close to sequential control of the three zones.

A significant advantage of the sequential dimming approach is its simplicity. A near flawless self-calibrating system could easily be configured using the multi-zone sequential approach by placing multiple wireless photosensors at or near the work plane, preferably near work locations. A target level is then entered for each sensor. The control system would then sequentially dim the lighting zones one at a time, beginning with the perimeter zone, and moving to the next interior zone when the currently controlled lighting zone reaches its off condition. This continues until one of these sensors reaches its target level, in which case the critical work plane location that governs the settings for that daylight condition has been established. As daylight decreases, the currently dimmed lighting zone would be raised until it reaches full output, at which time the next zone closer to the window is energized at minimum light output and increased until the target illuminance is met at all analysis points. At any point in time, only one of the dimmed rows is emitting a fraction of its full light output, with all other controlled rows set at either fully on or off. This type of control is very close in energy savings to the ideal multi-zone control provided by the computer model. The Penn State team plans to investigate the sequential control system's performance using ceiling-mounted photosensors, and to test performance in a real space with both ceiling and work plane photosensors in BP3. This sequential approach is likely to work best in relatively open spaces that do not have tall partitions that significantly obstruct the delivery of daylight to task locations.

Results

Both large single zone and multi-zone photosensor controlled electric lighting systems were shown to save energy in daylit spaces, with multi-zone control capable of reducing the lighting power required by as much as 30-50% under individual daylight conditions. These studies considered a lighting control system that switches zones off when sufficient levels of daylight are provided. On an annual basis in the spaces studied, multi-zone control of the same lighting equipment resulted in approximately 10-15% added savings compared to single zone control in a well-daylit open space with sidelighting. The multi-zone control system's performance indicates that these systems operate in a mode that is very close to sequential dimming of individual control zones. A test of optimized sequential control showed almost no reduction in energy savings compared to fully optimized multi-zone control. A sequentially controlled multi-zone lighting control system offers a system that is self-calibrating, simple, and accurate when applied with photosensors that are located at or near the work plane.

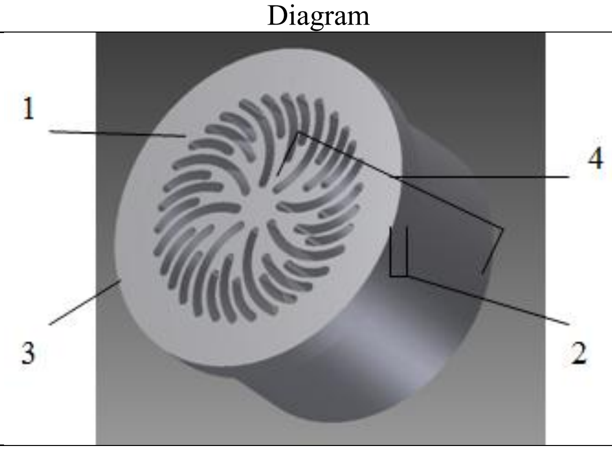
10. Swirl Diffusers

The research team at Morgan State University has designed and fabricated but has not yet demonstrated the hybrid ventilation system prototype. The model considers under-floor room air delivery throughout two levels of a commercial building, and swirl diffusers are the terminal units for the supply air. The prototype frame and swirl diffusers have been designed and fabricated, and the space is in the process of being developed with instrumentation. Demonstration at the laboratory level will be carried out in BP3. The project is currently at Stage 2 for small scale level demonstration and simulation processes.

The model space is a scale down of the front left end of Navy Yard Building 661, where it is assumed for experimentation that office spaces and laboratories will be developed on the first and second levels, respectively. Swirl diffusers will be implemented in the ventilation system, as the technology promotes effective entrainment of particles toward ceiling return ducts.

The swirl diffusers that have been implemented in the prototype were designed in Autodesk Inventor software with a 1-inch (25.4mm) diameter. The dimensions were established in units of mm, and they are listed in Table 9 below.

Table 9 Miniature Diffuser Dimensions

		Length (mm)	Diagram
	Grille		
1	Outer Diameter	25.4	
2	Depth	4.0	
	Casing		
3	Outer Diameter	28.4	
1	Inner Diameter	25.4	
4	Depth	18.0	

The swirl diffusers were designed and fabricated by rapid prototyping, and they were placed into the floor spaces as planned in the draft of diffuser placement. Ducts for supply and return air were added to the prototype model as well.

The use of swirl diffusers as the terminal unit from an under-floor air distribution system will be demonstrated in the university laboratory physically and through computer simulation in BP3 to study the indoor environmental quality and energy savings in an unoccupied space.