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Evaluation of Cellular Shades in the PNNL Lab Homes

November 2016

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Summary

To examine the energy performance of cellular shade window coverings, a field evaluation was undertaken in a matched pair of all-electric, factory-built “Lab Homes” located on the Pacific Northwest National Laboratory (PNNL) campus in Richland, Washington. The 1,500-square-foot homes are identical in construction and baseline performance, which allows any difference in energy and thermal performance between the baseline home and the experimental home to be attributed to the retrofit technology installed in the experimental home. The Lab Homes are in International Energy Conservation Code (IECC) climate zone 5, which is a heating dominated climate zone that also experiences hot summers. This is an ideal location for analysis of any technology that can save energy in both summer and winter.

To assess the performance of high-efficiency window attachments in a residential retrofit application, the energy use of each home was compared during the 2015-2016 winter heating season and both the 2015 and 2016 summer cooling seasons. Hunter Douglas Duette® Architella® Trielle™ opaque honeycomb “cellular” shades were installed on the interior side of the windows in the experimental home. The baseline home included two scenarios: one with no window coverings and the other with standard typical white vinyl horizontal blinds.

Different operational schedules were tested to help understand this effect on the heating, ventilation, and air conditioning (HVAC) energy use. The results from the different operational scenarios are detailed below.

1. Optimum Operation – The “optimum” operation schedule followed the Hunter Douglas-developed HD Green Mode operation schedule for the experimental period to maximize the energy savings, while minimizing the time the windows are covering the view of the outside. The HD Green Mode is a predefined schedule based on the installation latitude and the solar calendar. In this experimental scenario, the baseline home had no window attachments installed. During the heating experimental period, the cellular shades reduced the HVAC energy use by $14.4 \pm 2.0\%$. During the cooling experimental period, under similar test conditions, the cellular shades reduced the HVAC energy use by $14.8 \pm 2.1\%$.
2. Optimum Operation Compared to Vinyl – This experiment compared the HVAC energy use between the insulated cellular shades in the experimental home and typical white vinyl blinds in the baseline home, using the same HD Green Mode schedule as the previous experiment. During the heating season, the cellular shades reduced the HVAC energy use by $16.6 \pm 5.3\%$ when compared to standard vinyl blinds. During the cooling season, the cellular shades reduced the HVAC energy use by $15.3 \pm 2.9\%$.
3. Static Operation Compared to Vinyl – This experiment compared HVAC energy use between the cellular shades and typical white vinyl blinds. No operational schedules were implemented and both sets of window coverings remained closed for the duration of the experiment. The cellular shades installed in the experimental home reduced the HVAC energy use by $10.5 \pm 3.0\%$ in the heating season and $16.6 \pm 2.9\%$ in the cooling season.

The average effective reduction in window U-factor from the addition of the cellular shades on January 23, 2016 was about $0.22 \text{ Btu/hr ft}^2 \text{ }^\circ\text{F}$. Although this calculation is not statistically ideal, it does provide one data point as a reference for this technology going forward.

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Acronyms and Abbreviations

°F	degrees Fahrenheit
ACH50	air changes per hour at 50 Pascals of depressurization with respect to the outside
AERC	Attachments Energy Rating Council
BPA	Bonneville Power Administration
Btu	British thermal unit(s)
CEE	Center for Energy and Environment
cfm	cubic feet per minute
cfm50	cubic feet per minute at 50 Pascals of depressurization with respect to outside
CU	condensing unit
d	day(s)
DOE	U.S. Department of Energy
ft	foot (feet)
hr	hour(s)
HVAC	heating, ventilation, and air conditioning
IECC	International Energy Conservation Code
kW	kilowatt(s)
kWh	kilowatt hour(s)
LAN	local area network
LBNL	Lawrence Berkeley National Laboratory
NEEA	Northwest Energy Efficiency Alliance
NFRC	National Fenestration Rating Council
Pa	Pascal(s)
PGE	Portland General Electric
PNNL	Pacific Northwest National Laboratory
SEER	seasonal energy-efficiency ratio
SHGC	solar heat gain coefficient
VT	visible transmittance
W/m ²	watts per square meter
Wh	watt-hour(s)
yr	year(s)

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1.0 Introduction

Residential buildings in the United States currently require approximately 8 quadrillion Btu/yr of energy for heating and cooling, which accounts for about 40% of the primary energy consumed by homes.¹ Windows are a major thermal weak point in residential buildings because glass assemblies inherently have much higher heat loss than opaque surfaces with insulation. For example, it has been estimated that windows account for approximately 25% of the heating, ventilation, and air conditioning (HVAC) energy use in a typical residential building (Huang et al. 1999). Retrofitting and renovating existing homes to save energy has become an increasingly important component of U.S. energy strategy, and energy-efficient window attachments, such as high-efficiency shades², blinds³, low-e storm windows, or other window coverings, can significantly improve the thermal performance of a window at a fraction of the financial cost of a full window replacement. A honeycomb, or “cellular,” shade retrofit could potentially offer a cost-effective solution for improving a window’s thermal performance by interrupting and reducing heat transfer through the window.

This report describes whole-home experimental research conducted in support of Building America’s Window Attachments Program, the Northwest Energy Efficiency Alliance (NEEA), and the Bonneville Power Administration (BPA). The U.S. Department of Energy’s (DOE’s) Building America Program serves as a catalyst to accelerate the residential building energy-efficiency market transformation and support increasing levels of cost-effective whole-house energy savings. NEEA is an alliance of more than 140 Northwest utilities and energy-efficiency organizations working on behalf of more than 13 million energy consumers.⁴ Its mission is to accelerate both electric and gas energy efficiency, leveraging regional partnerships to advance the adoption of energy-efficient products. BPA is a public service organization that delivers efficient, economical, and reliable power to the Pacific Northwest.

This project evaluated the energy savings potential of installing cellular shades on the interior side of typical double-pane clear aluminum-frame windows in the Pacific Northwest National Laboratory’s (PNNL’s) matched pair of Lab Homes.⁵ Both homes have identical envelopes and deploy identical simulated occupancy schedules so that the performance and effects of the window attachments were isolated from all other variables.

¹ Based on 2013 reference case heating and cooling end use consumption from “Residential sector key indicators and consumption.” Annual Energy Outlook (DOE). Available online: <http://www.eia.gov/forecasts/aeo/pdf/tbla4.pdf>.

² Cellular shade is defined as a window covering made of pleated fabric that is “honeycombed” and can be raised and lowered. Their adjustability adds elements balancing view, privacy, glare control, and daylighting. Also called insulated cellular shade.

³ Blind is defined as a louvered window covering with stacked vanes that can be both tilted and raised/lowered.

⁴ See <http://neea.org/about-neea> for more information on NEEA.

⁵ See <http://labhomes.pnnl.gov> for more information on Lab Homes.

2.0 Background

Window attachments (e.g., window shades and blinds) have been used for privacy for centuries. Only recently, however, has attention been drawn to the energy savings potential achieved through increasing the insulating values of window coverings, and optimizing the solar gains added to the space. The type and selection of window attachment technologies has greatly expanded in recent years; however, limited information exists regarding the energy-saving characteristics of these products and currently no comprehensive rating system exists to help distinguish the energy-saving features of one window covering from another (Curcija et al. 2013).

Retrofitting and renovating existing homes to save energy has become an increasingly important component of the nation's energy strategy, and energy-efficient window attachments (e.g., cellular shades) offer an affordable way to significantly improve the thermal performance of a window. These high-efficiency window attachments can be an option for utilities (and homeowners) to consider as part of a package of retrofits to cost-effectively improve thermal performance and meet conservation goals. This study examines the energy-saving potential of installing cellular shades over double-pane clear-glass windows.

2.1 Window Attachment Technology

Typically, cellular shades are considered to have the highest R-value of all window attachments. Introduced in the 1980s, cellular shades are designed to trap air inside pockets that act as insulators and can increase the R-value of the window covering and reduce the thermal heat transfer through window that it covers (Ariosto et al. 2013). The specific technology examined as part of this study was the Hunter Douglas Duette® Architella® Trielle™ honeycomb fabric shade, made with six layers of fabric including two opaque layers and five insulating air pockets (see Figure 2.1). The insulating air pockets—and layer of metallized Mylar lining those pockets—minimizes conductive, convective, and radiant heat transfer, effectively increasing the R-value of the fabric.



Figure 2.1. Hunter Douglas Duette Architella Trielle Shades¹

¹ Photo Courtesy of Hunter Douglas: <http://www.hunterdouglas.com/honeycomb-shades/duette-architella>

2.2 Window Attachment Development and Previous Research

In 2013, the DOE sponsored a comprehensive energy modeling study led by Lawrence Berkeley National Laboratory (LBNL) that focused on a range of window attachments, including products such as shades, blinds, storm window panels, and surface-applied films simulated in four types of “typical” houses located in 12 characteristic climate zones. The simulations captured the optical and thermal complexities of these products (Curcija et al. 2013) and also considered typical operation and usage patterns based on a separate study focusing on user behavior with respect to operable window coverings (Bickel et al. 2013). The study found that many of the window attachments examined can yield significant energy savings when installed over windows; however, the degree of savings depends on the attachment type, baseline window conditions, seasonal and climate factors, and how the attachment is operated, when applicable. Nevertheless, the study concluded that in heating dominated climates, particularly in the north-central climate zones, low-e storm windows and insulated cellular shades are two of the most effective window attachments at reducing HVAC usage.

In addition to DOE’s research focusing on window coverings, a number of research institutions, energy-efficiency programs, and utilities have completed characterization and meta analyses¹ (Ariosto et al. 2013) and energy simulation analyses (CEE 2014; Garber-Slaght and Craven 2011; Zirnhelt et al. 2015) validating energy savings from cellular shades and other window attachments in multiple climate zones and prototype residential buildings (see Table 2.1). There have also been some field studies examining energy savings from cellular shades over aluminum-framed clear-glass windows (PGE 2015).

This side-by-side evaluation in the PNNL Lab Homes represents the first controlled whole-house experiments performed with cellular shading devices. The data collected as a result of the PNNL Lab Homes experiments can complement previous modeling and field studies to help describe the performance of cellular shades as a retrofit option for typical residential homes. The detailed results describe the performance of the cellular shades more precisely than field studies, because the experiments are not confounded by weather or occupancy impacts, and thus can potentially be used to calibrate whole-house energy models.

2.3 Advantages of PNNL Lab Homes Research

Although field data and case studies provide valuable insights related to the savings potential of window attachments in specific applications or climate zones, the variability that occurs due to home type and occupancy behavior can make it difficult to isolate the savings from the window attachment and project these savings to alternative circumstances. Controlled side-by-side experiments, such as those conducted in the PNNL Lab Homes, provide a platform for more detailed and comprehensive data collection on the HVAC energy performance of cellular shades. The PNNL Lab Homes provide controlled experimental HVAC data, which can be used to appropriately tailor and calibrate building simulation models to account for relevant interactions, occupancy, climate zones, and baseline characterizations.

¹ See, for example, the website: <http://www.efficientwindowcoverings.org/>, sponsored and developed by DOE, Building Green, and LBNL and DOE’s <http://energy.gov/energysaver/articles/energy-efficient-window-treatments>.

Table 2.1. Summary of Case Studies Focused on Window Attachments and Cellular Shades

Study	Sponsor	Technology Analyzed	Summary of Findings
Energy Savings from Window Shades (Zirnhelt et al. 2015)	Hunter Douglas and Rocky Mountain Institute	Hunter Douglas cellular shades	<ul style="list-style-type: none"> • Denver Max Cooling Savings – 25% • Denver Max Heating Savings – 10% • Peak electrical demand reduction of 9% for new homes • Increased thermal comfort
Evaluation of Residential Window Retrofit Solutions for Energy Efficiency (Aristo and Memari 2013)	The Pennsylvania Housing Research Center	Modeled cellular shades	<ul style="list-style-type: none"> • Reduction in U-factor of 38% • Reduction in SHGC of 39%
Residential Windows and Window Coverings (Bickel et al. 2013)	DOE Building Technologies Office	Behavior and window coverings installed base study	<ul style="list-style-type: none"> • 18% of northern climate homes have no coverings • 62% of all window attachments are blinds
Evaluating Window Insulation for Cold Climates (Garber-Slaght and Craven 2011)	Cold Climate Housing Research Center	Double cell cellular shades over double-pane clear window	<ul style="list-style-type: none"> • Modeled reduction in U-factor of 15% • Actual increase in R-value of 60%
Energy Savings from Window Attachments (Curcija et al. 2013)	DOE Building Technologies Office	Modeled a variety of cellular shades over double-pane clear window	<ul style="list-style-type: none"> • Reduction in U-factor of 0.06-0.29 • Reduction in SHGC of 0.11-0.44

3.0 Experimental Design

The evaluation of window attachments took place in the PNNL Lab Homes between July 2015 and September 2016. This section describes the experimental timeline, the Lab Homes, the window attachments used in the experiment, and the data collection and analysis methodologies.

3.1 Lab Homes

The experiments were conducted in PNNL’s side-by-side Lab Homes, which form a platform for precisely evaluating energy-saving and grid-responsive technologies in a controlled environment. The PNNL Lab Homes are two factory-built homes installed on PNNL’s campus in Richland, Washington. Each Lab Home has seven windows and two sliding glass doors, for a total of 196 ft² of window area. For the experiments examined in this study, the “experimental home” was retrofitted with Hunter Douglas honeycomb shades¹, while a matching “baseline home” was equipped with typical vinyl blinds² or no window coverings, depending on the experiment. The floor plan of the Lab Homes, as constructed, is shown in Figure 3.1.

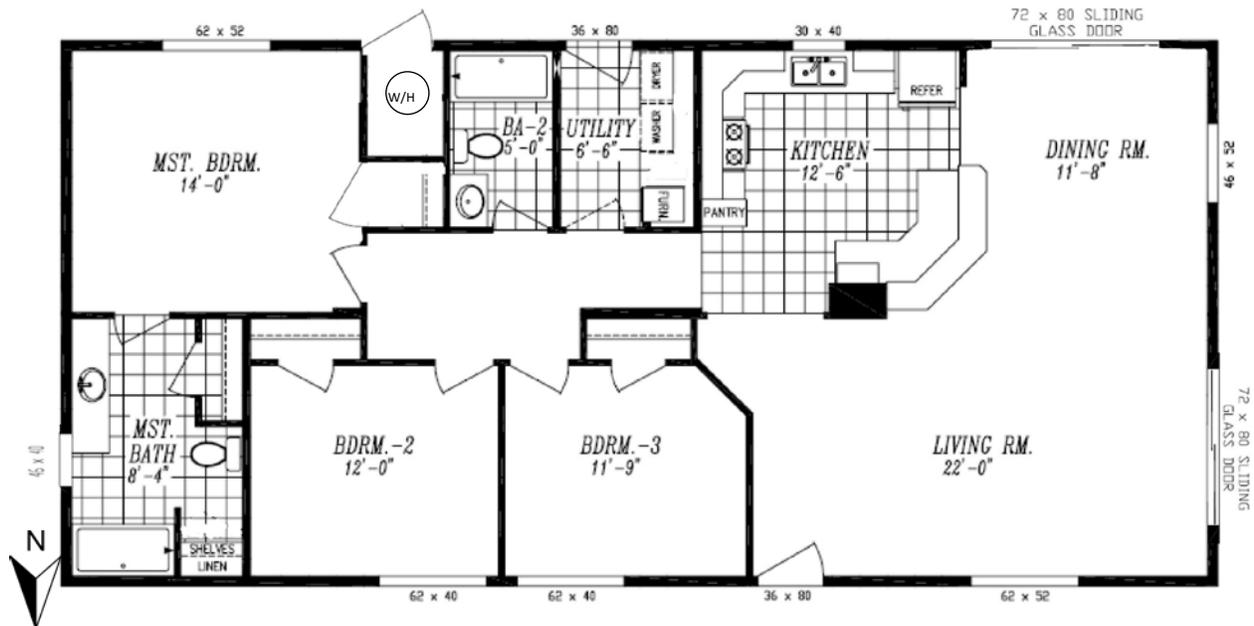


Figure 3.1. Floor Plan of the Lab Homes as Constructed

For the calibration period, the thermostat set point in the heating and cooling season was set to 71°F with no set-backs enabled on the Venstar T7850 smart thermostat. The set point was chosen to generate a large temperature differential between indoors and outdoors to maximize the observed HVAC impacts while keeping the set points in a range representative of real home occupancy conditions.

Within the Lab Homes, controllable breakers were programmed to activate connected loads on schedules to simulate human occupancy. The basis for occupancy simulation was data and analysis developed in previous residential simulation activities (Hendron and Engebrecht 2010; Christian et al. 2010). The

¹ Hunter Douglas Duette Architella Trielle honeycomb shades Fabric: C83 Trielle Daisy White.

² Where “typical” blinds are horizontal slatted “vinyl” style blinds with 1-in. slats.

occupancy schedules developed for this experiment were based specifically on the home style, square footage, and an assumed occupancy of three adults (see Appendix B). The per-person sensible heat generation and occupancy profiles were mapped from previous studies to be applicable to this demonstration.

Occupancy and connected-lighting heat generation were simulated by activating portable and fixed lighting fixtures throughout the home. Each bedroom was equipped with a table lamp to simulate human occupancy; occupancy and lighting loads in other areas of the home were simulated via fixed lighting. In both cases (portable and fixed lighting), schedules were programmed into the electrical panel for run times commensurate with identified use profiles. The enabled profiles sought to match daily total occupancy characteristics with less emphasis on defined hourly simulation. Equipment loads were simulated identically in both homes using electric resistance wall heaters in the living/dining room: one 500 W and one 1,500 W heater run simultaneously for a set number of minutes each hour. This set of experiments focused on sensible loads only; latent loads were not simulated and were not anticipated to significantly impact the performance of the cellular shades. More information on this can be found within Appendix B. The Lab Homes are each equipped with a 2.5-ton, 13 seasonal energy-efficiency ratio (SEER) heat pump that can be used for both heating and cooling. Alternatively, an electrical furnace can provide heat as well. To reduce the error and inefficiency between the baseline and experimental homes in the winter months, the electrical resistance furnace was the primary heat source used for these experiments.

3.2 Window Attachment Retrofit

The primary windows and patio doors currently installed in both of the Lab Homes are double-pane, clear-glass aluminum-frame sliders. For the experiment, window attachments were installed on the interior side of the experimental home's windows and sliding glass doors. The quantity and size specifications of the windows were as follows:

- 2 ea 62" × 52" – two-track sliders
- 2 ea 62" × 40" – two-track sliders
- 1 ea 30" × 40" – two-track sliders
- 1 ea 46" × 52" – two-track sliders
- 1 ea 46" × 40" – single hung
- 2 ea 72" × 80" – sliding glass doors

The cellular shades were installed over the primary windows such that the gap between the windows and the blind brackets was 1.5 in. Equipped with a battery pack and small motor, the shades had the ability to be automatically raised and lowered with predefined schedules programmed through the Hunter Douglas PowerView™ Motorization app. A Hunter Douglas local area network (LAN) was used to communicate to individual or groups of shades within the system. Wireless signals were sent via the LAN to specified window coverings to open and close on command. Due to the size of the Lab Homes, a signal wireless repeater was used to ensure that the communications between the programmed router and shades were effectively transmitted. Figure 3.2 details the installation location of one of the two mounting brackets and an example of the shade installed in the kitchen.



Figure 3.2. Mounting Bracket for the Cellular Shades (left) and Installed Hunter Douglas Cellular Shade (right)

3.2.1 Window Attachment Performance Ratings

The U-factors and solar heat gain coefficients (SHGC) for the primary windows are listed in Table 3.1 at NFRC standard size and conditions. Installing a shade behind a primary window will alter the SHGC, U-factor, and visible transmittance (VT). When fully closed, typical vinyl blinds are expected to decrease the U-factor of a double glazed window opening by approximately 0.07–0.13 Btu/hr-ft²-F and different types of cellular shades should reduce the U-factor by 0.06-0.29 Btu/hr-ft²-F (Curcija et al. 2013), as well as greatly reduce the SHGC and VT depending on the type of blind.

Table 3.1. Primary Window Characteristics

Value	Primary Windows in Lab Homes A and B	
	Windows	Patio Doors
U-factor (Btu/hr-ft ² -F)	0.68	0.66
SHGC	0.7	0.66
VT	0.73	0.71

Although the NFRC provides U-factor ratings for primary windows, there is currently no standard performance or energy-efficiency rating system that exists for window attachments, such as window shades. To address the lack of a nationally recognized rating system for window attachments and coverings, the Attachments Energy Rating Council (AERC)¹ was launched in 2015 with the support of the DOE. The mission of the AERC is to develop a third-party program that creates a consistent set of energy performance-based rating and certification standards and program procedures for energy-efficient window attachments. When complete, the AERC will oversee the implementation of rating, certification,

¹ <http://energy.gov/eere/buildings/downloads/attachments-energy-ratings-council> and <http://aercnet.org>.

labeling, and performance verification procedures. In addition, the AERC will develop and maintain a publicly available, searchable electronic database of window attachment product performance.

3.3 Experimental Timeline

A timeline of the operating parameters and experimental scenarios exercised during the data-collection periods is presented in Table 3.2. The cellular shades were first installed in July 2015, and ultimately removed in September 2016. In both the heating and cooling seasons, the cellular shades were evaluated with various operational modes and compared to two different baselines. Below are the experiments that were conducted for each season with a brief explanation of the process:

1. Optimum Operation – The “optimum” operation schedule followed the Hunter Douglas-developed HD Green Mode operation schedule (detailed in Appendix A) to maximize the energy savings from insulated window shades, while minimizing the time the windows are covering the view of the outside. The schedule was specifically designed to capitalize on thermal properties while optimizing consumer needs for natural daylight. In this experiment, the baseline home had no window attachments installed.

Table 3.2. Experimental Timeline

Description	Duration (days) ^(a)	First Season Date Range	Second Season Date Range
<u>Cooling Season Experiment Setup</u>			
Air-leakage testing	1	7/10/2015	
Baseline (no window attachments)	21	7/11/2015 – 7/22/2015	6/13/2016 – 7/4/2016
Installation of cellular shades	2	8/18/2015	7/4/2016
<u>Cooling Season Experiment</u>			
Cellular shades optimum operation	27	8/3/2015 – 8/15/2015	7/5/2016 – 7/31/2016
Cellular shades and vinyl blinds static operation	19	8/19/2015 – 9/2/2015	8/27/2016 – 9/29/2016 ^(b)
Cellular shades and vinyl blinds optimum operation comparison	17	9/3/2015 – 9/15/2015	9/3/2016 – 9/29/2016
<u>Heating Season Experiment Setup</u>			
Air-leakage test	1	11/16/2015	
Baseline	13	11/17/2015 – 12/7/2015	
<u>Heating Season Experiment</u>			
Cellular shades optimum operation	29	12/8/2015 – 1/5/2016	
Cellular shades and vinyl blinds static operation	17	1/23/2016 – 2/8/2016	
Cellular shades and vinyl blinds optimum operation	7	2/9/2016 – 2/15/2016	
Remove cellular shades	1	2/16/2016	

(a) Duration includes the combined experimental days of both seasons
(b) Completed in parallel with optimum operation comparison by leaving the shades drawn over the weekends

2. Optimum Operation Compared to Vinyl Blinds – This experiment quantified the impact of an “optimized” cellular shade schedule in the experimental home, compared to typical vinyl slatted blinds in the baseline home. The window coverings in both Lab Homes (baseline and experimental homes) were set to follow the HD Green Mode operational schedule for the experimental period.
3. Static Operation Compared to Vinyl Blinds – This experiment compared the impact on HVAC energy use between the insulated cellular shades and typical vinyl slatted blinds during the heating and

cooling seasons. No operational schedules were implemented and both sets of window coverings remained closed for the duration of the experiment.

The interior blinds in the baseline home were typical white vinyl horizontal slatted venetian blinds over the windows and vertically hung slat blinds over the sliding glass doors. These were chosen to be representative of blinds that would be found in a typical production home. In vinyl slat blinds, the slats can both be raised / lowered and rotated at different angles, creating many possible states between fully open and fully closed. For the purpose of this study, the “closed” state was with the blind lowered completely and the slats rotated to block as much light as possible. During experiments that used the “HD Green Mode” schedule, PNNL researchers manually opened and closed the attachments in the baseline home to correspond exactly with the automated “HD Green Mode” schedule. Per the schedule in Appendix A, adjustments were made 4 to 7 times per day depending on the month. Researchers were careful to minimize entry and exit time so as to minimize any impact on energy use in the baseline home.

3.4 Metering and Simulated Occupancy

Metering and system-control activities take place at both the electrical panel and at the end-use location. All metering was completed using Campbell Scientific data loggers and matching sensors. Two Campbell data loggers were installed in each home, one allocated to electrical measurements (Table 3.3) and one to temperature and other data collection (Table 3.4). The tables below highlight the equipment being monitored, the location of the sensor, the monitored variables, and the data application. Data from all sensors were collected via cellular modems that were individually connected to each of the loggers.

All data were captured at 1-minute intervals by the Campbell Scientific data loggers. These 1-minute data were averaged over hourly and daily time intervals to afford different analyses.

Occupancy in the homes was simulated via a programmable commercial lighting breaker panel (one per home) using motorized breakers. These breakers were programmed to activate connected loads on schedules to simulate human occupancy by introducing heat to the space.

To help understand the dynamic flow of heat between the outside and inside of each home, advanced metering techniques were used to catalog the temperature at points both on the primary window and in the space between the primary window and window attachment. Figure 3.3 displays the temperature measurement points that were placed on one window facing each cardinal direction, except east.

Table 3.3. Electrical Points Monitored

Performance Metric	Location of Sensors	Monitored Variables	Data Application
Whole Building Energy Use	Electrical panel mains	kW, amps, volts	Comparison between homes of <ul style="list-style-type: none"> power profiles time-series energy use differences and savings
HVAC Energy Use (heat pump for cooling and forced-air furnace for heating)	Panel metering compressor	kW, amps, volts	Comparison and difference calculations between systems of <ul style="list-style-type: none"> power profiles time-series energy use differences and savings
	Panel metering air handling unit	kW, amps, volts	
	End-use metering condensing unit (CU) fan/controls	kW, amps, volts	
	Panel metering of furnace elements	kW, amps, volts	
HVAC Energy Use (ventilation)	Panel metering of three ventilation breakers (two bathroom and whole-house fans)	kW, amps, volts	Comparison and difference calculations between systems of <ul style="list-style-type: none"> power profiles time-series energy use differences and savings
Appliances and Lighting	Panel metering of all appliance and lighting breakers	kW, amps, volts	Comparison and difference calculations.

Table 3.4. Temperature and Environmental Points Monitored

Performance Metric	Location of Sensors	Monitored Variables	Data Application
Space Temperatures	13 Ceiling-hung thermocouples/1–2 sensors per room/area, and 1 HVAC duct supply temperature per home	Temp. (°F)	Comparison and difference calculations between homes of <ul style="list-style-type: none"> temperature profiles time-series temperature changes
	2 mean radiant sensors per home (main living area, master bedroom)	Temp. (°F)	
Glass Surface Temperatures	22 thermocouples (2 sensors per window interior/exterior center of glass); west window with 6 sensors. 2 thermocouples per home to measure temperature between the primary and storm windows.	Temp. (°F)	Comparison and difference calculations between homes of <ul style="list-style-type: none"> temperature profiles time-series temperature changes
Through-Glass Solar Radiation	1 pyranometer sensor per home trained on west-facing window	W/m ²	Comparison and difference calculations between homes of <ul style="list-style-type: none"> profiles by window and location

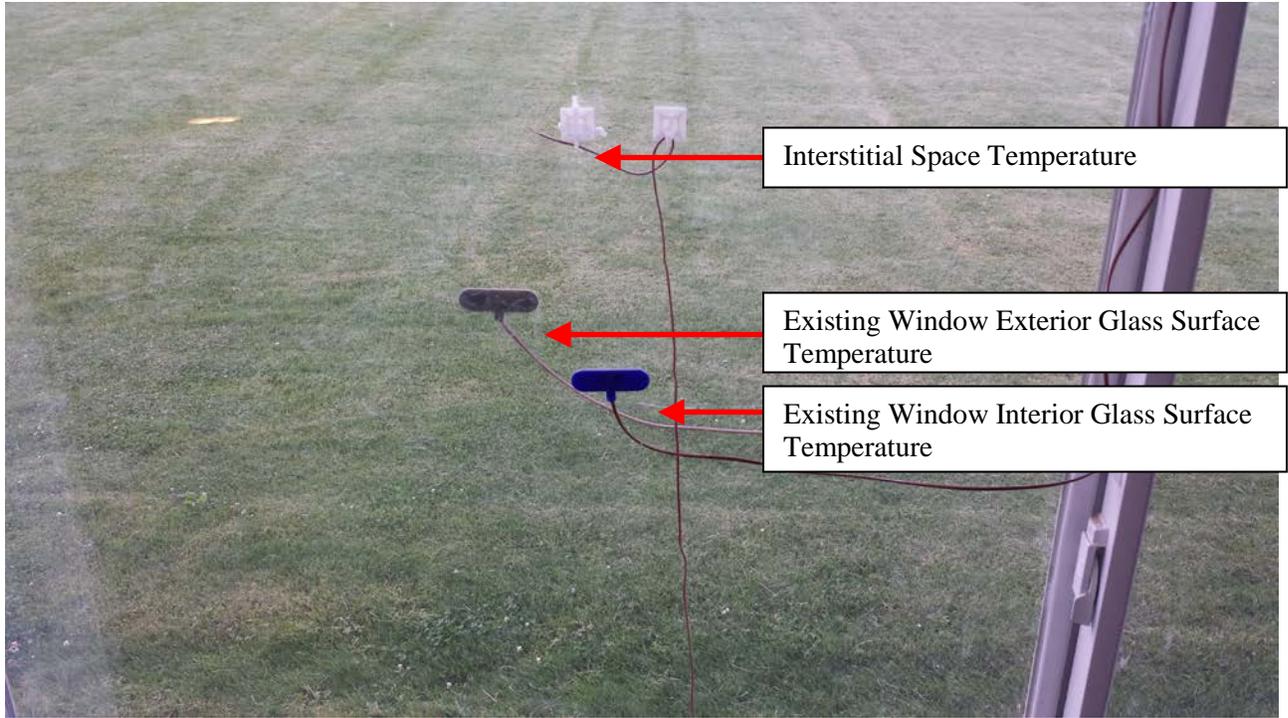


Figure 3.3. Window Temperature Measurement Points

4.0 Results and Discussion

This section summarizes the energy usage performance of the two homes during a calibration period when the experimental home is equipped with 3 in. cellular shades and the baseline home is equipped with either no attachments or typical vinyl blinds. Most experimental results are presented as daily averages with 95% confidence intervals calculated for each measured quantity, assuming a normal distribution of the data and applying a student's t-statistic. The 95% confidence interval is then used to establish the significance of the differences observed as a result of the window attachment retrofit by applying a traditional significance test.

4.1 Side-by-Side Calibration Period

Prior to installing the window attachments for both the heating and cooling seasons, performance data was collected to determine the baseline performance of both homes over 13 days during the heating season and 21 days during the cooling season.

The calibrated difference in HVAC energy use between the homes appears to increase as the homes age. One theory is that differing settling patterns of wall insulation and degradation of HVAC efficiency have led to this discrepancy. To help minimize this potential discrepancy for this experiment, general maintenance was completed on the HVAC system and envelope of each home prior to the calibration period.

Over the 34-day calibration period, the baseline home used an average of $4.33 \pm 1.02\%$ more HVAC energy per day than the experimental home. This difference in energy use between the homes is significant enough that the HVAC savings described in this report have been modified to reflect the offset. Figure 4.1 and Figure 4.2 depict the HVAC energy use of each home as a function of the outdoor air temperature. The HVAC energy use differential between the two homes appears to be greater in the colder outdoor weather as the outdoor air temperature drops.

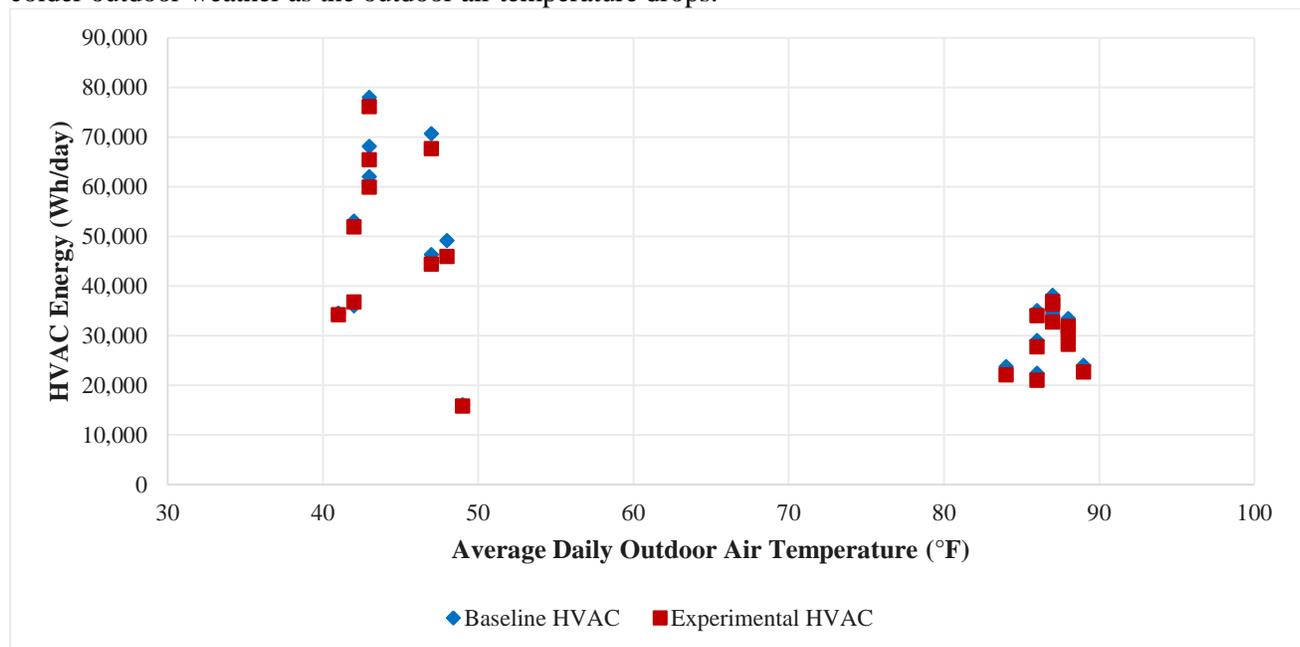


Figure 4.1. HVAC Energy Use of the Baseline HVAC and the Experimental HVAC during the Heating and Cooling Season Calibration Period

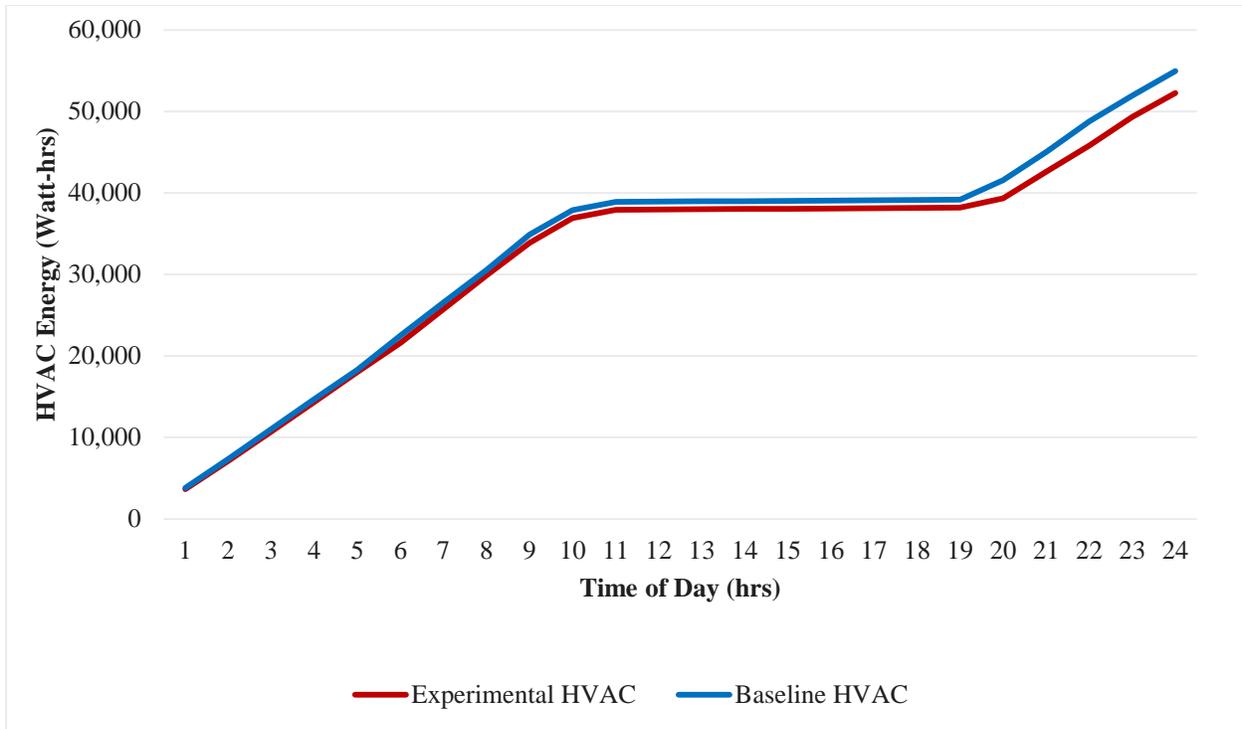


Figure 4.2. Cumulative HVAC Energy Use of the Experimental Home (red) and the Baseline Home (blue) throughout One Heating Season Day of the Calibration Period

4.1.1 Building Shell Air-Leakage Calibration

Building shell air leakage in both Lab Homes was measured before beginning the experiment to obtain a baseline reading on the homes and ensure equivalent air-leakage performance between the two homes. Prior to the window attachment installation, a blower door test¹ was conducted on each home. The baseline home had an air-leakage rate of 789.7 ± 25.7 cfm at 50 Pa depressurization (cfm50) with respect to the outside, and the experimental home had an air leakage of 820.1 ± 26.5 cfm50. Accounting for experimental error in the blower door measurement and the blower door instrument accuracy, the two homes demonstrated similar air-leakage rates with 95% confidence prior to installing the cellular shades in the experimental home. The calculated air changes per hour at 50 Pa (ACH₅₀) depressurization with respect to the outside and air changes per hour at normal pressurization (ACH_n) are also presented in Table 4.1.

After installation of the Hunter Douglas cellular shades in the experimental home, the air-leakage rate was retested. Air leakage in the experimental home measured 822.0 ± 24.7 cfm50. This indicates that installation of the cellular shades did not significantly impact air leakage in the experimental home.

¹ Blower door testing equipment measures flow with an accuracy of $\pm 3\%$.

<http://www.energyconservatory.com/products/automated-blower-door-systems-and-accessories>

Table 4.1. Blower Door Test Results Prior to Window Attachment Installation

Parameter	Baseline Home		Experimental Home	
	Average Value	95% Confidence Interval	Average Value	95% Confidence Interval
cfm50 ^(a)	789.7	25.7	820.1	26.5
ACH50	3.80	0.12	3.95	0.13
ACH _n ^(b)	0.18	0.01	0.18	0.01

(a) Cubic feet per minute at 50 Pascals of depressurization
(b) n = 21.5, based on single-story home in climate zone 3, with minimal shielding

4.2 Heating Season Results

Heating during the winter was provided solely by a forced-air electric resistance furnace. Although a variety of heating systems and fuel types are used in homes, using electric resistance heating allows precise direct measurement of thermal energy impact of the window attachments in the Lab Home experiments because the electric resistance elements are 100% efficient. These results can then be easily extrapolated to other heating system types based on the relative efficiency of those systems. The performance of the window attachments during the heating season was evaluated from December 2015 to February 2016.

To compare and assess the performance of the cellular shades relative to the baseline windows, energy use was compared on an average daily basis.

4.2.1 Heating Season – Optimum Operation

HVAC savings through the implementation of the HD Green Mode operational schedule (detailed in Appendix A) was compared between the experimental home with the cellular shades and the baseline home with no window attachments installed over a series of 29 experimental days between December 8, 2015 and January 5, 2016. Over this experimental period, the average outdoor air temperature was 33.9°F. The HVAC energy usage was cataloged to determine the total reduction in HVAC use between the two Lab Homes due to the cellular shades with optimum schedule implementation. During the heating season, the HD Green Mode operation schedule is specifically designed to optimize the amount of solar heat gain and ensure that adequate light enters the interior, but also uses the cellular shade’s insulating properties to reduce the amount of heat loss through windows when no solar gain is expected. It should be noted, however, that because the schedules are pre-programmed and do not respond to actual solar gain, they will raise during a certain time of the day, regardless of whether it is cloudy or sunny at that time. In the experimental home, wirelessly controlled motors within the shades followed the pre-programmed schedule. Verification of the scheduled operation was done by Lab Homes researchers. During this experimental period, the cellular shades reduced the HVAC energy use of the experimental home by 8,602 ±977 Wh or 14.4 ±2.0% compared to baseline home where no blinds were installed.

Figure 4.3 details a single day, December 18, 2015, during the experimental period in which the window attachments followed the HD Green Mode operational schedule. On this day, the average outdoor air temperature was 34°F, and the thermostat set point for each Lab Home was 71°F. The HVAC energy use in watt-hours for the baseline home (dark blue) and the experimental home (red) are shown along with the outdoor air temperature (green) and representative indoor temperature for the baseline home (purple) and the experimental home (gray). The HVAC load profile is the total HVAC energy usage averaged over each hour. The HVAC savings for each experimental day is averaged over the total experimental period to develop the average daily HVAC energy consumption.

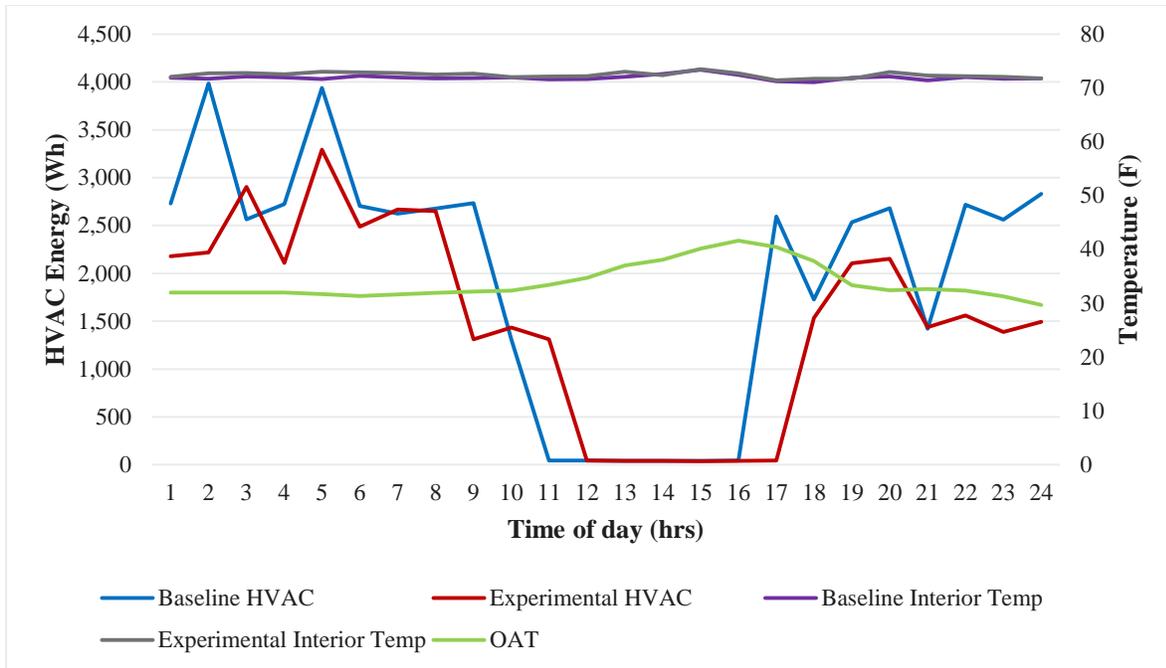


Figure 4.3. HVAC Usage during Implementation of the HD Green Mode Optimum Schedule between Cellular Shades in the Experimental Home (red) and No Window Attachments in the Baseline Home (blue)

4.2.2 Heating Season – Optimum Operation Compared to Vinyl Blinds

During these experiments, cellular shades and typical vinyl blinds were both operated according to the HD Green Mode operational schedule. This experiment was completed over a series of 7 days between February 9, 2016 and February 15, 2016. Over this experimental period, the average outdoor air temperature was 46.6°F. In the experimental home, wirelessly controlled motors within the cellular shades operated them according to the pre-programmed HD Green Mode schedule, and in the baseline home, the same operation schedule was implemented manually. Verification of the scheduled operation was done by Lab Homes researchers as the baseline home’s blinds changed state. When compared to typical vinyl blinds in the baseline home, the cellular shades reduced the daily average HVAC load in the experimental home by an average of $5,766 \pm 1420$ Wh or $16.6 \pm 5.3\%$ during the experimental period. The large margin of error is again due to limited number of experimental days and the variation in daily HVAC savings.

Figure 4.4 details a single day (February 12, 2016) during the experimental period where the window attachments followed the HD Green Mode operational schedule detailed in Appendix A. On this day, the average outdoor air temperature was 45.2°F. The HVAC energy use in watt-hours for the baseline (blue) and experimental home (red) are shown along with the outdoor air temperature (green).

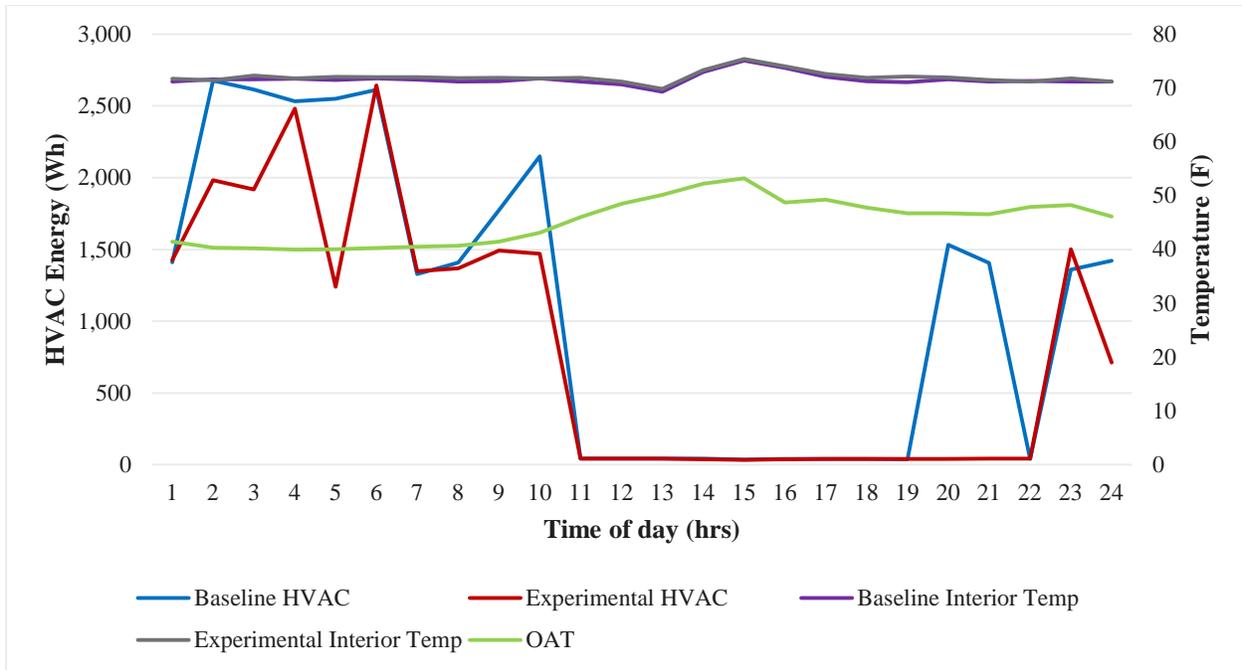


Figure 4.4. HVAC Usage during Implementation of the HD Green Mode Optimum Schedule between Hunter Douglas Cellular Shades Compared to Vinyl Blinds (February 12, 2016)

4.2.3 Heating Season – Static Operation

Comparison of the cellular shades to typical vinyl binds with static operation was completed over 17 experimental days between January 23, 2016 and February 8, 2016. The HVAC energy usage was cataloged and compared to determine the average daily reduction in HVAC use during this time. The cellular shades reduced the HVAC energy usage in the experimental lab home by an average $4,510 \pm 1,089$ Wh or $10.5 \pm 3.0\%$ when compared to the standard vinyl blinds installed in the baseline home. The margin of error, within the 95% confidence interval, is due to limited number of experimental days and the variation in daily HVAC savings observed over the experimental period.

Figure 4.5 shows data from January 25, 2016, where the window attachments were left closed for the full day. On this day, the average outdoor air temperature was 33.7°F . The HVAC energy use in watt-hours for baseline home (dark blue) and experimental home (red) are shown along with the outdoor air temperature (green) and representative indoor temperature for the baseline home (purple) and experimental home (gray). The HVAC load profile is the total HVAC energy usage averaged over each hour. The HVAC savings for each experimental day is averaged over the total experimental period to develop the average daily HVAC energy consumption.

During the early morning hours of the day, the reduction in HVAC load due to the insulating feature of the cellular shades can be seen on Figure 4.5. On January 25, 2016, sunrise was at 7:27 am. After about 9:00 am, solar gains were strong enough that the envelope of the both Lab Homes were heated toward the indoor set point (of 71°F) and HVAC operation was almost identical. At about 10 a.m., the solar heat gains are enough for the homes to reach the set point (and eventually, beyond the set point) with no HVAC energy use. For reference, the interior temperature distributions between the two homes can be seen in Figure 4.6 for static operation during the heating season.

The insulating property of cellular shades traps additional heat within the interior space. Throughout the day, solar gains will affect the internal temperature of both of the homes. This can be seen early afternoon of January 25, 2016. As the sun begins to set and the building envelope begins to cool, the experimental home retains temperature increases above the thermostat set point longer into the evening.

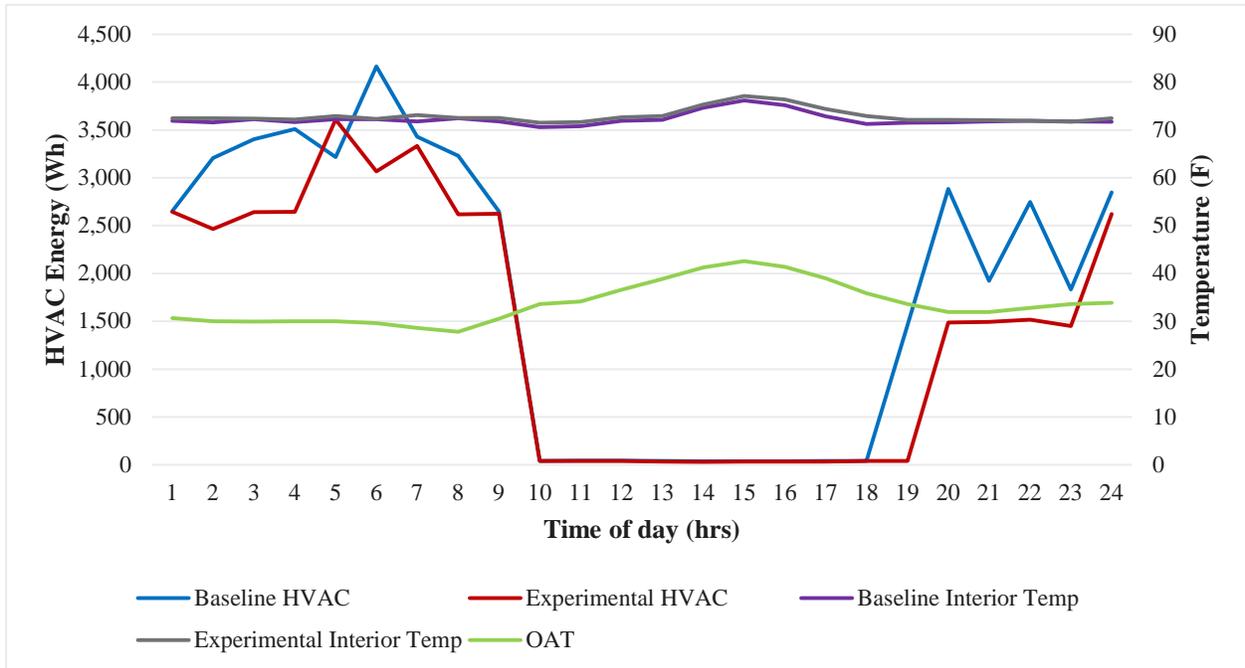


Figure 4.5. HVAC Usage during Implementation of the Static Schedule between Cellular Shades in the Experimental Home (red) and Standard Vinyl Blinds in the Baseline Home (blue)

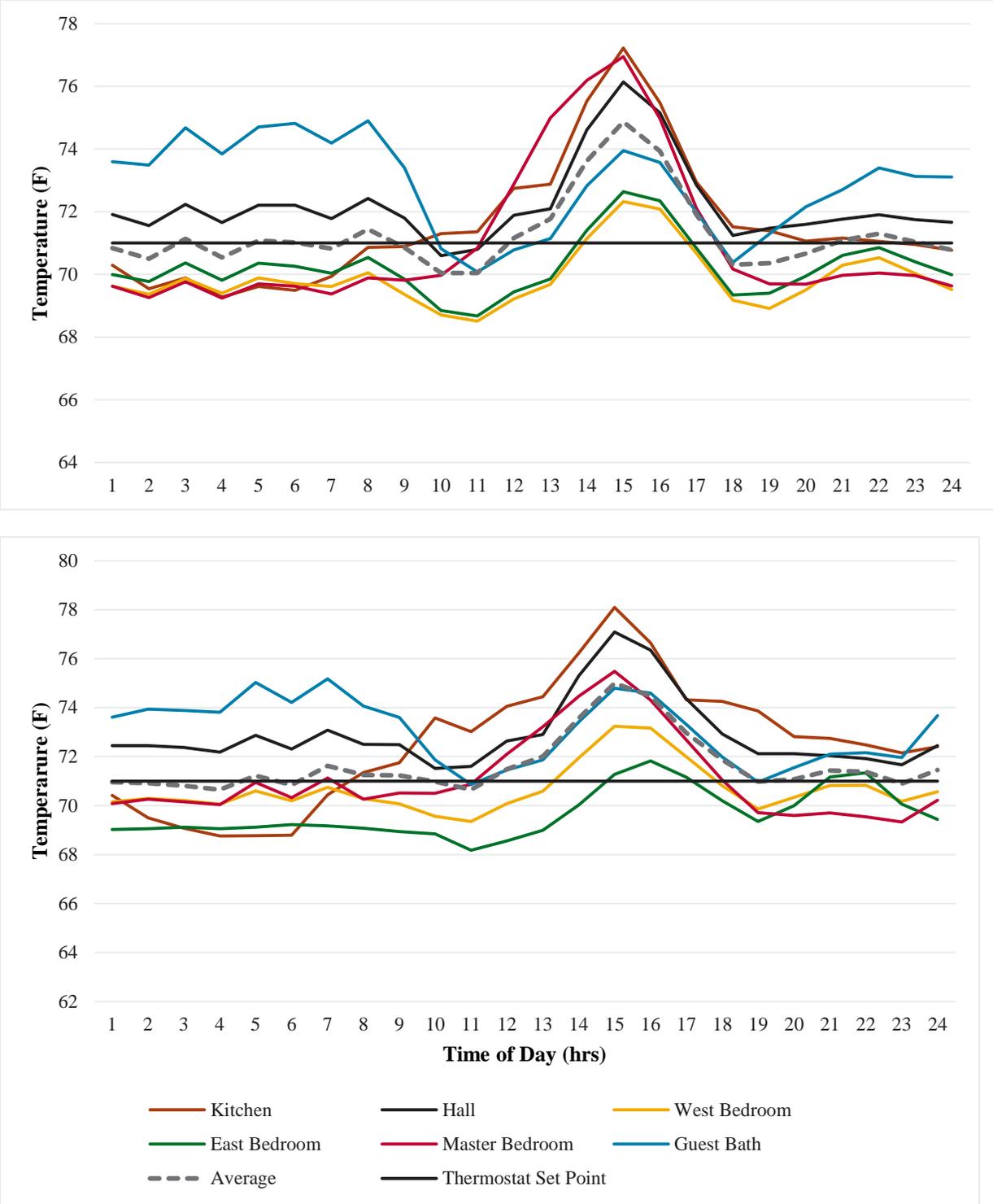


Figure 4.6. Interior Temperature of the Baseline Home (top) Compared to the Experimental Home (bottom) during Static Operation on January 25, 2016. Straight line indicates thermostat set point.

4.3 Cooling Season Results

Cooling season experimental data was collected from July to September 2015 and June to September 2016. Cooling during the summer was provided to both Lab Homes with a 2.5-ton, 13 SEER heat pump. To compare and assess the performance of the cellular shades relative to the baseline windows, energy use is reported as average daily savings.

4.3.1 Cooling Season – Optimum Operation

HVAC savings through the implementation of the HD Green Mode operational schedule were compared between the experimental home with the cellular shades and the baseline home with no window attachments installed over a series of 21 experimental days between August 3 and August 15, 2015 and July 5 and July 31, 2016. Verification of the scheduled operation was done by Lab Homes researchers.

Over this experimental period, the average outdoor air temperature was 76.6°F and the cellular shades reduced the average daily HVAC energy use in the experimental home by 4,498 ±631 Wh or 14.8 ±2.1% compared to HVAC energy use in the baseline home where no blinds were installed.

Figure 4.7 details a representative day, July 23, 2016, during the experimental period where the window attachments followed the HD Green Mode operational schedule detailed in Appendix A. On this day, during a 24-hour period, the average indoor air temperature was 71.9°F, peaking at 86°F in the late afternoon.

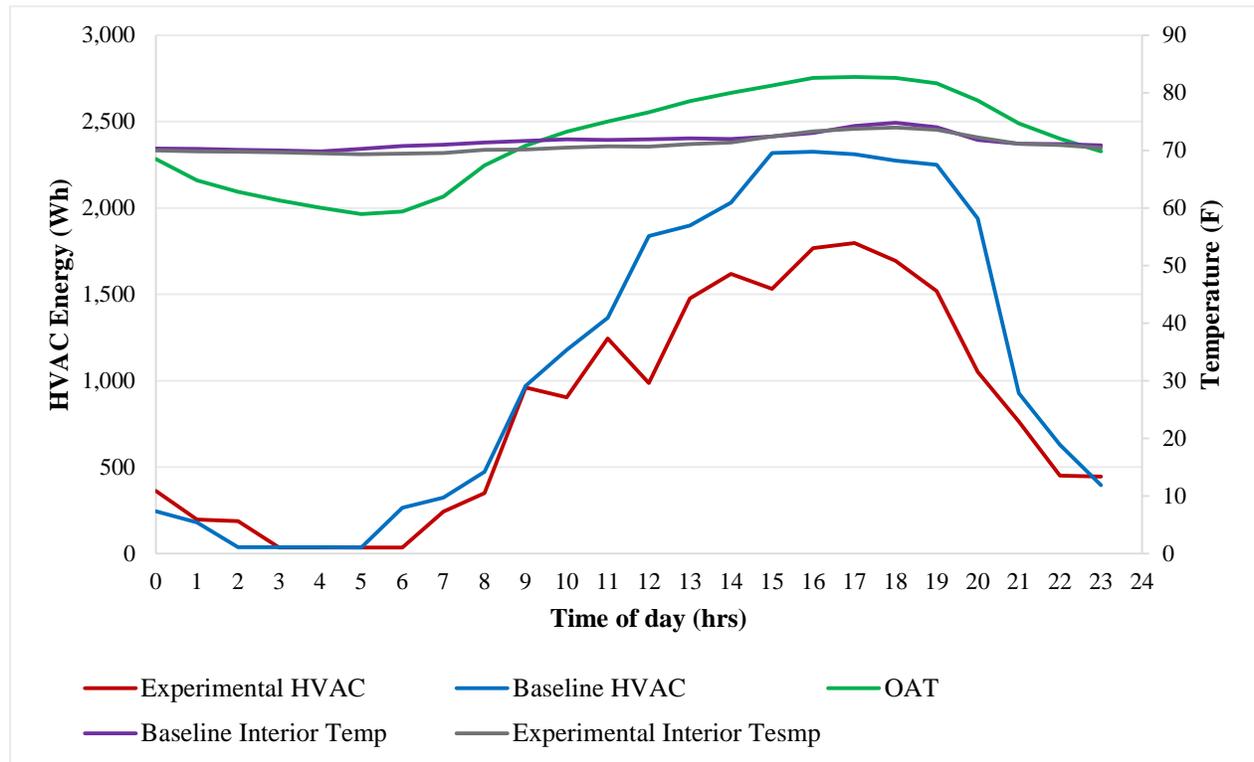


Figure 4.7. HVAC Usage during Implementation of the HD Green Mode Optimum Schedule between Cellular Shades in the Experimental Home (red) Compared to No Window Attachments in the Baseline Home (blue) on July 23, 2016

The internal set point of each of the Lab Homes was 71°F. The HVAC energy use in watt-hours for baseline home (dark blue) and experimental home (red) are shown along with the outdoor air temperature (green) and representative indoor temperature for the baseline home (purple) and experimental home (gray). The HVAC load profile is the total HVAC energy usage averaged over each hour. The HVAC savings for each experimental day is averaged over the total experimental period to develop the average daily HVAC energy savings.

During the cooling season, the peak HVAC load was in the afternoon and evening. The reduction in peak HVAC energy use can be seen between the experimental and baseline Lab Homes. The ambient temperature increased above the thermostat set point at 10:00 am. The HVAC system began to cycle on each hour after sunrise (5:28 am). The cellular shades continue to provide HVAC savings late into the evening (sunset 8:36 pm).

4.3.2 Cooling Season – Optimum Operation Compared to Vinyl Blinds

During the optimum operation experiments, cellular shades and typical vinyl blinds were both operated according to the HD Green Mode operational schedule. This experiment was completed over a series of 17 days between September 3 and September 15, 2015 as well as between September 3 and September 29, 2016. Over this experimental period, the average outdoor air temperature was 64.1°F. The decreased outdoor air temperature over the experimental period greatly reduced the HVAC load for both Lab Homes. The HVAC energy usage was cataloged to determine the reduction in HVAC energy use between the two window coverings during the schedule implementation. During the cooling season, the HD green schedule was specifically designed to reduce the amount of solar heat gain while ensuring adequate light enters the interior by keeping some window coverings open at all times. When compared to typical vinyl blinds in the baseline home, the cellular shades reduced the peak HVAC load by an average of 3,211 ±600 Wh or 15.3 ±2.9%.

Figure 4.8 details a single day, September 11, 2015, during the experimental period where the window attachments in both homes followed the HD Green Mode operational schedule. On this day, the average outdoor air temperature over a 24-hour period was 72°F, with an early evening peak temperature of 80°F. The HVAC energy use in watt-hours for the baseline (blue) and experimental home (red) are shown along with the outdoor air temperature (green).

Figure 4.8 shows the lower HVAC energy use in the experimental home compared to the baseline home. This is because the baseline home's vinyl blinds allowed more heat to be transferred through the drawn window attachments into the home. The greater solar heat gain was compensated for with increased HVAC energy use.

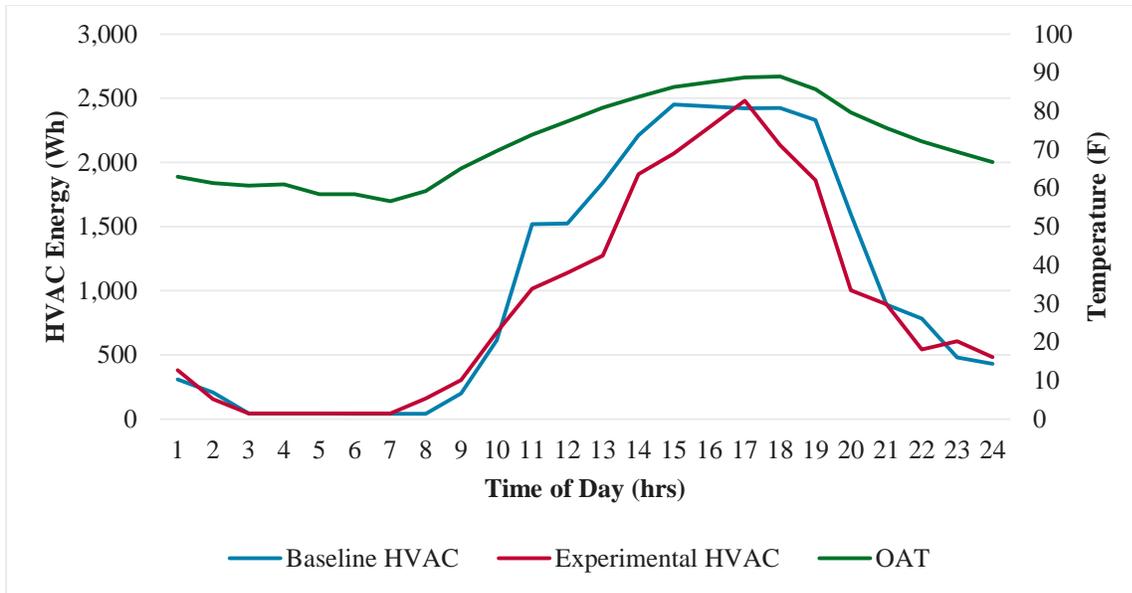


Figure 4.8. HVAC Usage during Implementation of the HD Green Mode Optimum Schedule between Cellular Shades in Experimental Home Compared to Vinyl Blinds in Baseline Home (September 11, 2015)

4.3.3 Cooling Season – Static Operation Compared to Vinyl Blinds

Comparison of the cellular shades to the typical vinyl binds was completed over 19 experimental days between August 19, 2015 and September 2, 2015 and August 27, 2016 and September 29, 2016. The HVAC energy usage was cataloged and compared to determine the reduction in HVAC use during this time. The higher insulating values and lower total solar transmittance associated with cellular shades reduced the HVAC energy usage in the experimental home by an average of $3,557 \pm 500$ Wh or $16.6 \pm 2.9\%$ when compared to the energy use in the baseline home where standard vinyl blinds were installed and drawn closed.

Figure 4.9 shows data from August 27, 2015, where the window attachments were left closed for the full day. On this day, the average outdoor air temperature was 79.8°F with a high temperature of 96°F . The HVAC energy use in watt-hours for baseline home (dark blue) and experimental home (red) are shown along with the outdoor air temperature (green) and representative indoor temperature for the baseline home (purple) and experimental home (gray).

During the early morning hours, the HVAC systems performed similarly due to the fact that the ambient temperature was near 71°F and the sun had not yet come up. On August 27, 2015, sunrise was at 6:18 am. After this point, the envelope of the Lab Homes began to heat toward the set point and HVAC operation was almost identical. At about 9 am, solar heat gains began to drive up the cooling energy in both homes. The baseline home had greater peak HVAC demand over a longer duration compared to the experimental home. For reference, the interior temperature distributions between the two homes can be seen in Figure 4.10.

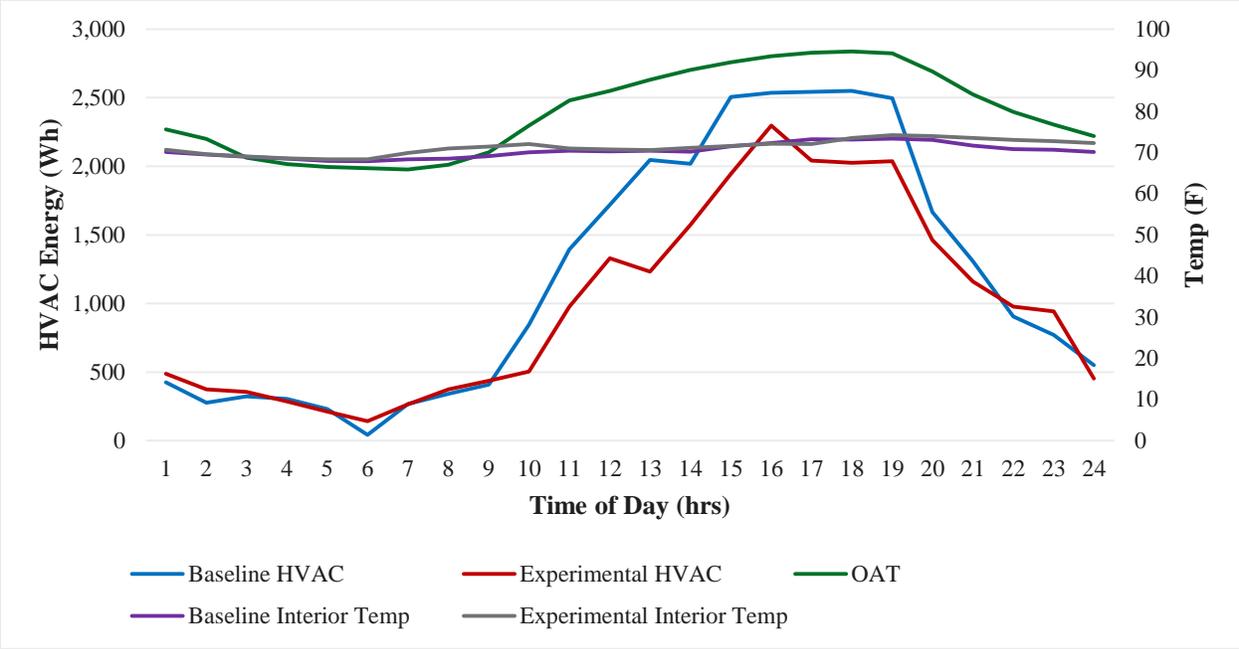


Figure 4.9. Cellular Shades in Experimental Home Compared to Vinyl Blinds in the Baseline Home, Both with Static Operation

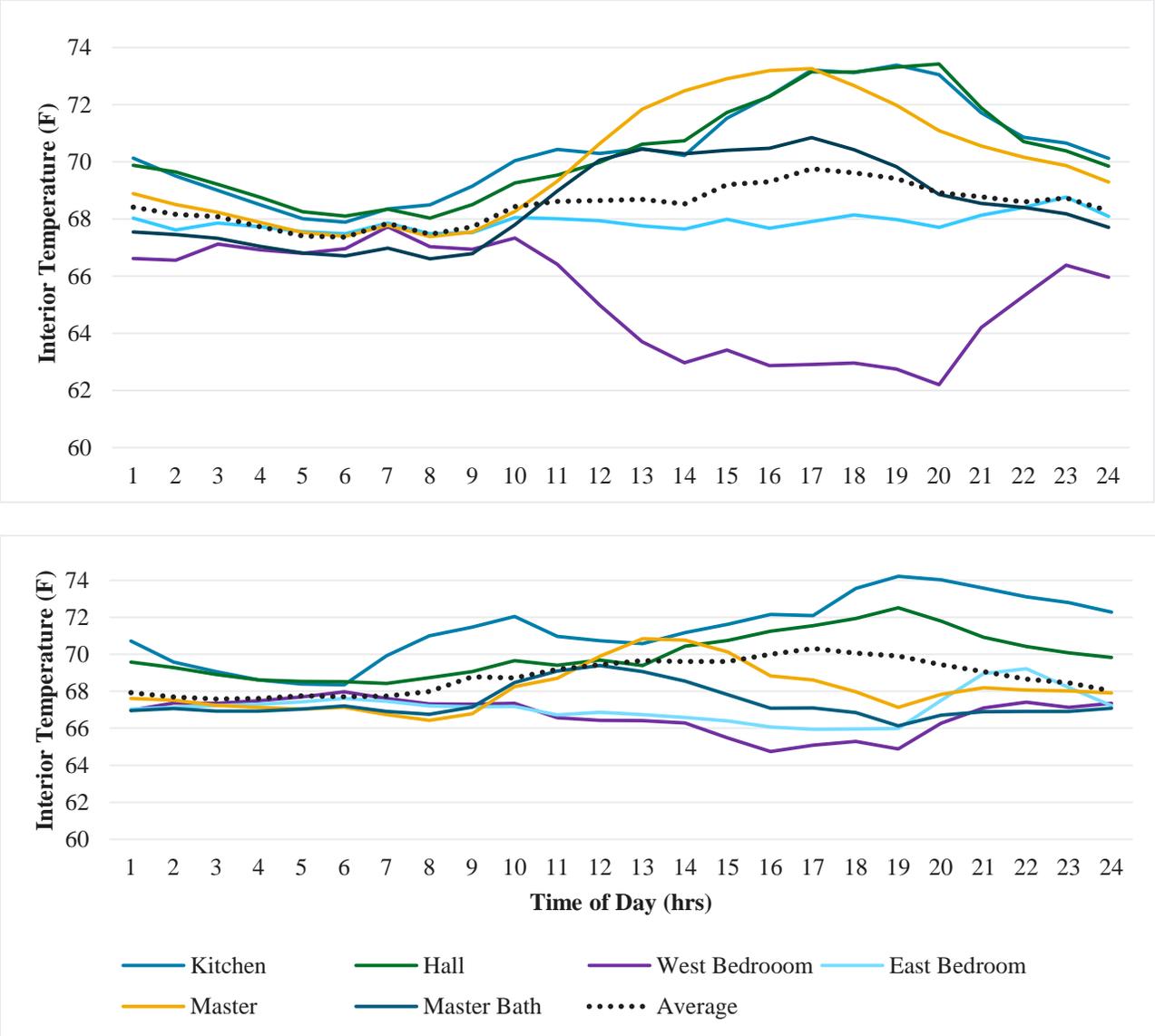


Figure 4.10. Interior Temperature of the Baseline Home (top) Compared to the Experimental (bottom) during the August 27, 2015, Static Window Attachment Comparison

5.0 Heat Transfer

The side-by-side Lab Homes provide an opportunity to understand the difference between the heat transferred through the windows of the homes, both with and without cellular shades. Figure 5.1 and Figure 5.2 show that at any given time, the HVAC system from one home could be on and the other system could be off.

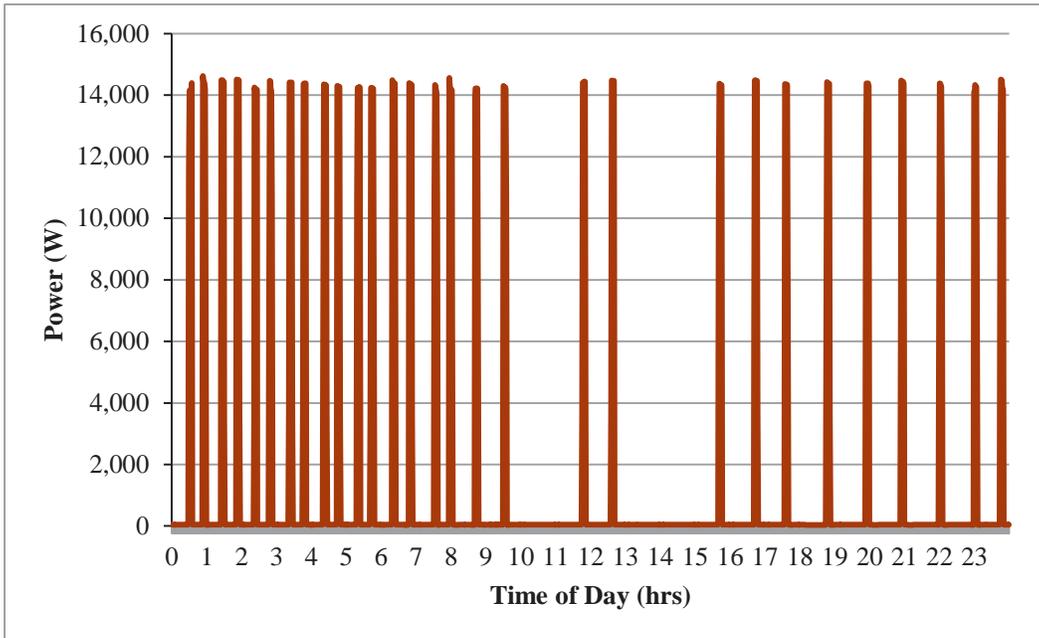


Figure 5.1. Sample HVAC Energy Use without Shades (January 23, 2016)

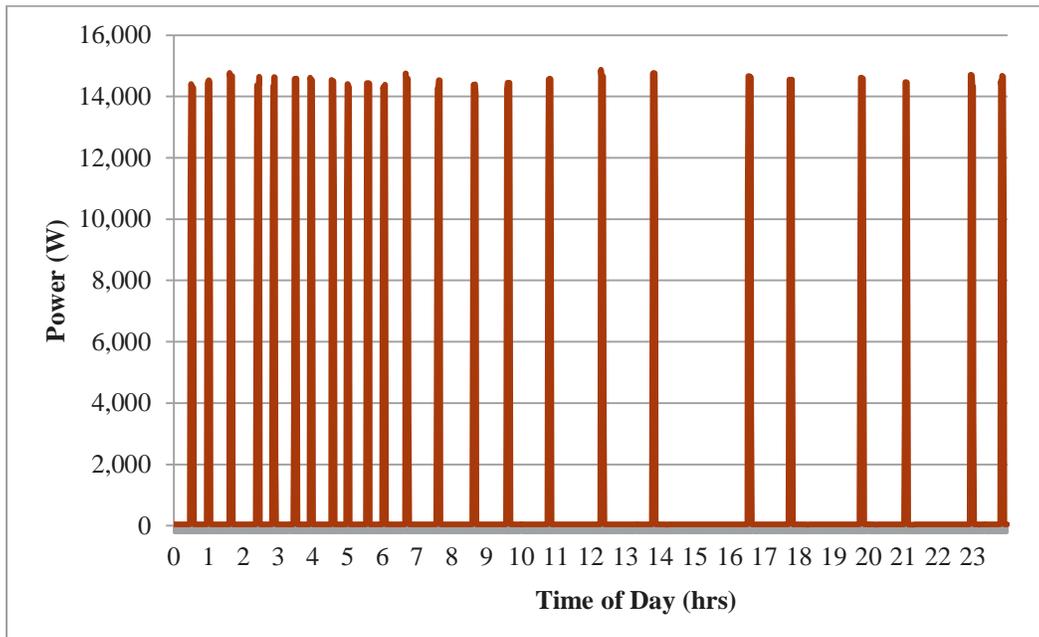


Figure 5.2. Sample HVAC Energy Use with Shades Closed All Day (January 23, 2016)

So, the instantaneous difference in the heat transferred from the homes is not an ideal variable to review. Instead the heat transfer coefficient should be averaged over the course of a day.

A simplified steady-state heat balance for each home under winter conditions can be expressed as in Equation 5.1:

$$\begin{aligned} Q_{\text{heating input}} + Q_{\text{solar gain input}} &= Q_{\text{window heat loss}} + Q_{\text{opaque envelope heat loss}} \\ &= U_{\text{windows}} A_{\text{windows}} (T_{\text{in}} - T_{\text{out}}) + Q_{\text{opaque envelope heat loss}} \end{aligned} \quad (5.1)$$

where U_{windows} is the overall average heat transfer coefficient for the windows and sliding glass doors including the effects of any window attachments.

If we assume that the Lab Homes have nearly identical enclosures (adjusting for minor differences through the calibration factor below), experience the same outdoor and indoor temperatures, that the heat transfer through the windows is one dimensional, and use only data taken at night (such that $Q_{\text{solar gain input}}$ is zero), then we can use the difference in HVAC heating input between the baseline and experimental homes to estimate the difference in window U-factor from the addition of the cellular shades. This is shown in Equation 5.2. The equation calculates the difference in the average heat transferred between the two homes for the night-hours on January 23, 2016. This date was the only day when the weather was relatively cold, and the cellular shades were closed for the entire period, and there were no window attachments at all in the baseline home. The sunrise and sunset on this date were 7:29 am and 4:48 pm respectively. The data used here only included data from the time interval of midnight to 7 am and 6 pm to 11:59 pm so that any effects from the sun were definitely avoided.

$$\overline{Q_{wos}} - \overline{Q_{ws}(CF)} = \overline{\Delta U_{shade}} A_s (\overline{T_{in}} - \overline{T_{out}}) \quad (5.2)$$

where

- Q_{wos} = the total heat transferred per day between the inside and the outside of the baseline home “without shades” (W or Btu/hr);
- Q_{ws} = the total heat transferred per day between the inside and the outside of the experimental home “with shades” (W or Btu/hr);
- CF = the heating season calibration factor based on the calibration period where both homes were run in identical scenarios. For this experiment, in this equation, the heating season calibration factor is 1.044 (4.4%).
- ΔU_{shade} = $U_{wos} - U_{ws}$ = the difference in overall heat transfer coefficient of the combined window and shade assembly, including the air gap between the window and the shade, compared to the window only (Btu/hr ft² °F);
- A_s = the area of the shades (ft²);
- T_{in} = the indoor temperature (°F); and
- T_{out} = the outdoor temperature (°F).

The results from this equation show that the average effective reduction in window U-factor from the addition of the cellular shades on January 23, 2016 was about 0.22 Btu/hr ft² °F. This is *roughly* a 33% reduction from the area-weighted average U-factor of the primary windows and doors (0.67), but it should be noted that this is not an exact comparison. NFRC U-factors are determined at standard sizes and environmental conditions, including specified indoor and outdoor temperatures and wind speed. Because the actual conditions and window sizes differ from the NFRC standardized conditions, the comparison is only approximate. Nonetheless, the reduction of 0.22 Btu/hr ft² °F is within the 0.06–0.29 Btu/hr-ft²-F range of reduction estimated by Curcija et al for different types of cellular shades when used over double glazed windows. (Curcija et al. 2013) Although this exercise is not statistically ideal, it does provide one data point as a reference for this technology going forward. Ideally, the experiment would have been run

for enough days to have an error band lower than 5%. In the future, for enclosure components, this data will be collected to ensure more accurate heat transfer properties.

6.0 Conclusions

This experiment used two side-by-side Lab Homes on the PNNL campus to measure the potential energy savings of window attachment products within different operational schedules in an experimental home compared to a baseline home equipped with standard double-pane clear-glass, aluminum-frame windows and sliding clear-glass patio doors. The windows in the baseline home are representative of many existing homes across the Pacific Northwest and much of the United States. Different operational schedules were tested to help understand the effect of the window attachment technology on the HVAC energy use. The experiments were completed in the 2015/2016 heating and cooling seasons and are summarized below with the associated HVAC energy savings.

The first cooling season experiments suffered from mild weather toward the end of the cooling season when the outdoor air temperature was close to the indoor thermostat set point. As a result, large amounts of HVAC load variability were observed between different experimental days, which increased the variability in the savings, and thus the uncertainty. The restricted timeframe also limited the amount of data that could be gathered, which increased the error associated with the savings confidence interval. Both of these challenges had an overall impact on the confidence of and statistical validity of the results, as shown in Table 5.1. It should be noted however, that the uncertainty in savings is, in all cases, much smaller than the magnitude of the savings.

Table 5.1. Summary of Experimental Results of Cellular Shades Compared to a Baseline on the Same Schedule

Experiment	Description	Season	Estimated Savings
Optimum Operation	Hunter Douglas blinds operated per the HD green schedule compared to no window attachments on the baseline home.	Cooling	14.8 ±2.1%
		Heating	14.4% ±2.0%
Optimum Operation Compared to Vinyl	Hunter Douglas blinds operated per the HD green schedule compared to standard vinyl blinds operated per the HD Green Mode on the baseline home.	Cooling	15.3±2.9%
		Heating	16.6±5.3%
Static Operation Compared to Vinyl	Hunter Douglas blinds compared to standard vinyl blinds. Both remained closed for the duration of the experiment.	Cooling	16.6±2.9%
		Heating	10.5±3.0%

The results consistently show both cooling and heating season energy savings associated with the use of cellular shades compared to both no window attachments and typical vinyl horizontal slat blinds. However, because of the experimental variability, it is more difficult to draw strong conclusions about differences in savings between the three different test operation protocols. Static operation with the shades closed all the time will minimize solar gains at all times (although this will also block all view and reduce daylight). This should in theory give the largest summer cooling savings, but also lower the winter heating savings somewhat by not taking advantage of beneficial solar gains to offset heating demand in the winter. In contrast, the optimized operation schedule should in theory balance cooling savings, heating savings, and view. It does appear that the optimized schedule delivered increased heating savings and similar cooling savings while also providing daylight and view, although it must be stressed that the statistical variability of the results limit the certainty of this conclusion.

The average effective reduction in window U-factor from the addition of the cellular shades on January 23, 2016 was about 0.22 Btu/hr ft² °F. Although this exercise is not statistically ideal, the results do provide one data point as a reference for this technology going forward.

This evaluation has added to the body of knowledge about window attachments by presenting measureable energy savings in a controlled setting. Results from this study clearly show that cellular shades are viable energy retrofits in single-family residences and should be explored further across a variety of building types and climate zones.

7.0 Future Work

Some utility energy-efficiency program researchers have expressed concern that the energy savings potential of operable fenestration attachments is limited by the necessary manual actions of the homeowner. To address this concern, PNNL has submitted a successful proposal to the BPA Technology Innovation program to examine auto-shading devices under varied operational schedules. The results of this project will determine the extent to which varied schedules impact HVAC load and lead to recommended operating strategies and the development of control algorithms that take input signals from sensors and the local thermostat to adjust dynamic components of shading devices. This work will be in coordination with Hunter Douglas's motorization team and include development of algorithms on open transactive platforms, such as the VOLTTRONTM platform.¹

In the future, cellular shades could also be added to energy modeling software so that the performance of these window attachments could be extrapolated across a variety of building types and climate zones and help determine the economic viability of specific window attachments in a variety of retrofit scenarios.

¹ The VOLTTRONTM platform is a distributed control and sensing software platform designed to manage a wide range of applications within the grid and buildings environment.

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Appendix A

HD Green Mode Operation Schedule

Appendix A

HD Green Mode Operation Schedule

Developed by Hunter Douglas, the HD Green Mode operation schedule is based on the solar calendar and the latitude of the location at which the window attachments are installed. The schedule is specifically designed to optimize HVAC operation and solar heat gain while allowing adequate light into the conditioned space. During the heating season, the schedule is optimized by the solar heat gain to the conditioned space and provides insulating values for the envelope during the evening. During the cooling season, the schedule is optimized to minimize the solar heat gain to the space.

Table A.1. Optimum Efficiency Window Covering Timetable for Richland, Washington (46° Latitude)

Month	Hours Window Coverings Are Open (Raised or Stacked)			
	North Facing	South Facing	East Facing	West Facing
January	Closed All Day	9:00 am–3:00 pm	8:00–11:00 am	1:00–4:00 pm
February	Closed All Day	8:00 am–4:00 pm	8:00–11:00 am	1:00–4:00 pm
March	Closed All Day	8:00 am–3:00 pm	7:00–11:00 am	2:00–5:00 pm
April	Closed All Day	8:00 am–4:00 pm	6:00–10:00 am	3:00–6:00 pm
May	2:00–7:00 pm	9:00–11:00 am	6:00–9:00 am	11:00 am–2:00 pm
June	11:00 am–1:00 pm	8:00–11:00 am	6:00–8:00 am 1:00–7:00 pm	10:00 am–1:00 pm
July	9:00 am–12:00 pm	7:00–10:00 am	6:00–7:00 am 12:00–7:00 pm	8:00 am–12:00 pm
August	9:00 am–12:00 pm	6:00–10:00 am	6:00–7:00 am 12:00–6:00 pm	8:00 am–12:00 pm
September	1:00–5:00 pm	8:00–10:00 am 4:00–5:00 pm	7:00–8:00 am	10:00 am–1:00 pm
October	2:00–4:00 pm	8:00 am–2:00 pm	8:00–10:00 am	3:00–5:00 pm
November	Closed All Day	9:00 am–3:00 pm	8:00–11:00 am	1:00–4:00 pm
December	Closed All Day	9:00 am–3:00 pm	9:00–11:00 am	1:00–3:00 pm

All times for timetable operation assume direct sunlight. During cloudy hours when outside temperature is 60°F or less, all shades should be closed, overriding the time tables.

Heating season testing should be performed alternating between timetable operation (with adjustment for cloudy hours) and shades closed 24/7. We suggest 7- to 10 day periods for each method of operation.

Cooling season testing should alternate between timetable operation (no adjustment needed for cloudy hours) and shades closed 24/7. Again, 7- to 10-day test periods are recommended.

Appendix B

Occupancy Simulation: Electrical Loads

Appendix B

Occupancy Simulation: Electrical Loads

Controllable breakers were programmed to activate connected loads on schedules to simulate human occupancy. The bases for occupancy simulation were data and analysis developed in previous residential simulation activities (Hendron and Engebrecht 2010; Christian et al. 2010). The occupancy simulations and schedules developed here were based specifically on the home style, square footage, and an assumed occupancy of three adults. The per-person sensible heat generation and occupancy profiles were mapped from previous studies to be applicable to this demonstration.

Occupancy and connected-lighting heat generation were simulated by activating portable and fixed lighting fixtures throughout the home. Each bedroom was equipped with a table lamp to simulate human occupancy; occupancy and lighting loads in other areas of the home were simulated via fixed lighting. In both cases (portable and fixed lighting), schedules were programmed into the electrical panel for run times commensurate with identified use profiles. The enabled profiles sought to match daily total occupancy characteristics with less emphasis on defined hourly simulation. Equipment loads were simulated identically in both homes using electric resistance wall heaters in the living/dining room: one 500 W and one 1,500 W heater run simultaneously for a set number of minutes each hour. This set of experiments focused on sensible loads only; latent loads were not simulated and were not anticipated to significantly impact the performance of the heat pump water heater. Table B.1, Table B.2, and Table B.3 present the load simulation and occupancy schedules for the Lab Homes heat pump water heater experiments.

The occupancy simulation protocol was robustly commissioned and verified daily throughout the baseline development and data-collection periods. Following each table, an example of occupancy schedule agreement is depicted from real data collected during the baseline period (Figure B.1, Figure B.2, and Figure B.3). The loads agree between homes and across days within ~1%.

Throughout the experiment, the heating, ventilating, and air conditioning systems were operated identically in the two homes. The 2.5-ton, 13 seasonal energy-efficiency ratio heat pumps maintained an interior set point of 76°F with no setback, as per Building America House Simulation Protocols (Hendron and Engebrecht 2010).

Table B.1. Daily Occupancy Schedules and Simulated Load

Time of Day	Simulation Strategy	Simulated Watts	Load Locations
1:00 am–7:00 am	Three 60 W table lamps	180	Lamps in master and each bedroom
7:00 am–8:00 am	Three 60 W table lamps	180	Lamps in master and each bedroom
8:00 am–9:00 am	One 60 W table lamp	60	Lamp in master bedroom
9:00 am–4:00 pm	One 60 W table lamp	60	Lamp in master bedroom
4:00 pm–5:00 pm	One 60 W table lamp	60	Lamp in master bedroom
5:00 pm–6:00 pm	Two 60 W table lamps	120	Lamps in master and East bedroom
6:00 pm–9:00 pm	Three 60 W table lamps	180	Lamps in master and each bedroom
9:00 pm–12:00 am	Three 60 W table lamps	180	Lamps in master and each bedroom
Wattage Total		3,180	

Table B.2. Daily Lighting Schedules and Simulated Load

Time of Day	Simulation Strategy	Simulated Watts	Load Locations
1:00 am–4:00 am	Ceiling fixture, 1 60-W lamp	60	Hall fixture
4:00 am –5:00 am	Ceiling fixture, 2 60-W lamps	120	Entry and living room fixtures
5:00 am–6:00 am	Two ceiling fixtures, two 60-W lamps each	240	Kitchen fixtures
6:00 am–7:00 am	Two ceiling fixtures, two 60-W lamps each	240	Kitchen fixtures
7:00 am–8:00 am	Two ceiling fixtures, two 60-W lamps each	240	Kitchen fixtures
8:00 am–9:00 am	Ceiling fixture, two 60-W lamps	120	Kitchen fixtures
9:00 am–3:00 pm	Ceiling fixture, one 60-W lamp	60	Hall fixture
3:00 pm–4:00 pm	Ceiling fixture, two 60-W lamps	120	Entry and living room fixtures
4:00 pm–5:00 pm	Two ceiling fixtures, two 60-W lamps each	240	Kitchen fixtures
5:00 pm–6:00 pm	Three ceiling fixtures, two 60-W lamps each	360	Kitchen and entry fixtures
6:00 pm–7:00 pm	Five ceiling fixtures, two 60-W lamps each	600	Master, kitchen, and two bedroom fixtures
7:00 pm–8:00 pm	Five ceiling fixtures, two 60-Watt lamps each	600	Master, kitchen, and two bedroom fixtures
8:00 pm–9:00 pm	Five ceiling fixtures, two 60-W lamps each	600	Master, kitchen, and two bedroom fixtures
9:00 pm–10:00 pm	Four ceiling fixtures, three 60-W lamps each	420	Master, kitchen, and hall fixtures
10:00 pm–11:00 pm	Two ceiling fixtures, two 60-W lamps each	240	Kitchen fixtures
11:00 pm–12:00 am	Ceiling fixture, one 60-W lamp	60	Hall fixture
Wattage Total		4,800	

Table B.3. Daily Equipment Schedules and Simulated Load

Time of Day	Simulation Strategy	Duration of Load (Minutes)	Simulated Watts	Load Locations
1:00 am–2:00 am	One 500 W & one 1,500 W wall heater	5	170	Living/dining room
2:00 am–3:00 am	One 500 W & one 1,500 W wall heater	5	157	Living/dining room
3:00 am–4:00 am	One 500 W & one 1,500 W wall heater	4	149	Living/dining room
4:00 am–5:00 am	One 500 W & one 1,500 W wall heater	4	148	Living/dining room
5:00 am–6:00 am	One 500 W & one 1,500 W wall heater	4	147	Living/dining room
6:00 am–7:00 am	One 500 W & one 1,500 W wall heater	5	181	Living/dining room
7:00 am–8:00 am	One 500 W & one 1,500 W wall heater	8	258	Living/dining room
8:00 am–9:00 am	One 500 W & one 1,500 W wall heater	9	284	Living/dining room
9:00 am–3:00 pm	One 500 W & one 1,500 W wall heater	8	268	Living/dining room
3:00 pm–4:00 pm	One 500 W & one 1,500 W wall heater	8	250	Living/dining room
4:00 pm–5:00 pm	One 500 W & one 1,500 W wall heater	7	243	Living/dining room
5:00 pm–6:00 pm	One 500 W & one 1,500 W wall heater	7	236	Living/dining room
6:00 pm–7:00 pm	One 500 W & one 1,500 W wall heater	7	229	Living/dining room
7:00 pm–8:00 pm	One 500 W & one 1,500 W wall heater	7	222	Living/dining room
8:00 pm–9:00 pm	One 500 W & one 1,500 W wall heater	7	235	Living/dining room
9:00 pm–10:00 pm	One 500 W & one 1,500 W wall heater	7	220	Living/dining room
10:00 pm–11:00 pm	One 500 W & one 1,500 W wall heater	8	282	Living/dining room
11:00 pm–12:00 am	One 500 W & one 1,500 W wall heater	11	356	Living/dining room
Wattage Total			5,875	

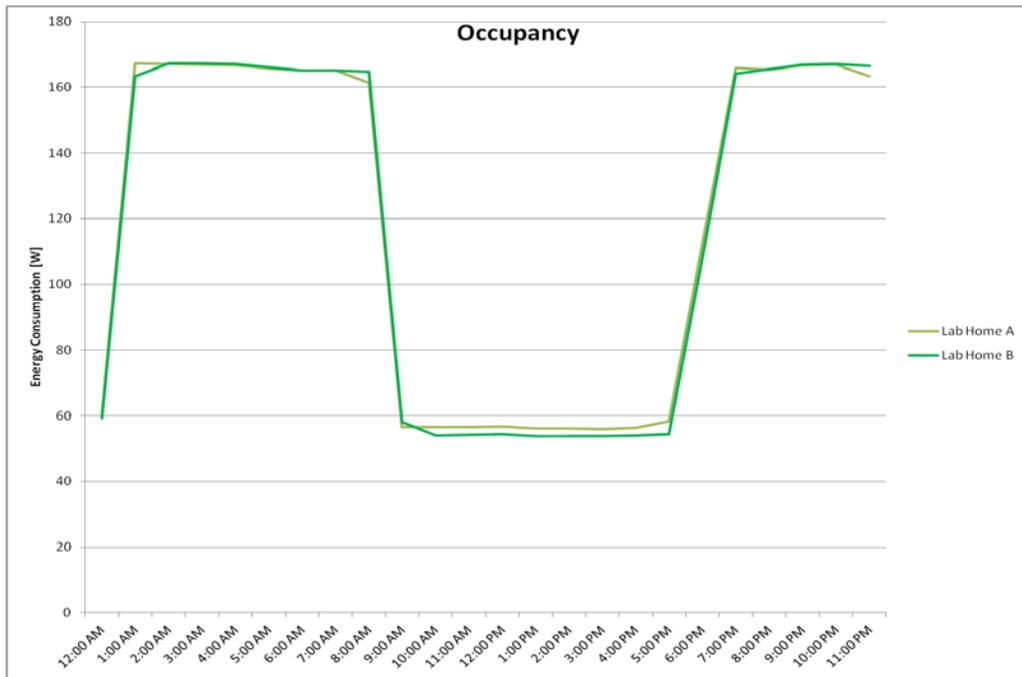


Figure B.1. Hourly Average Energy Consumption (W) Associated with Human Occupancy for an Example Day during the Baseline Period

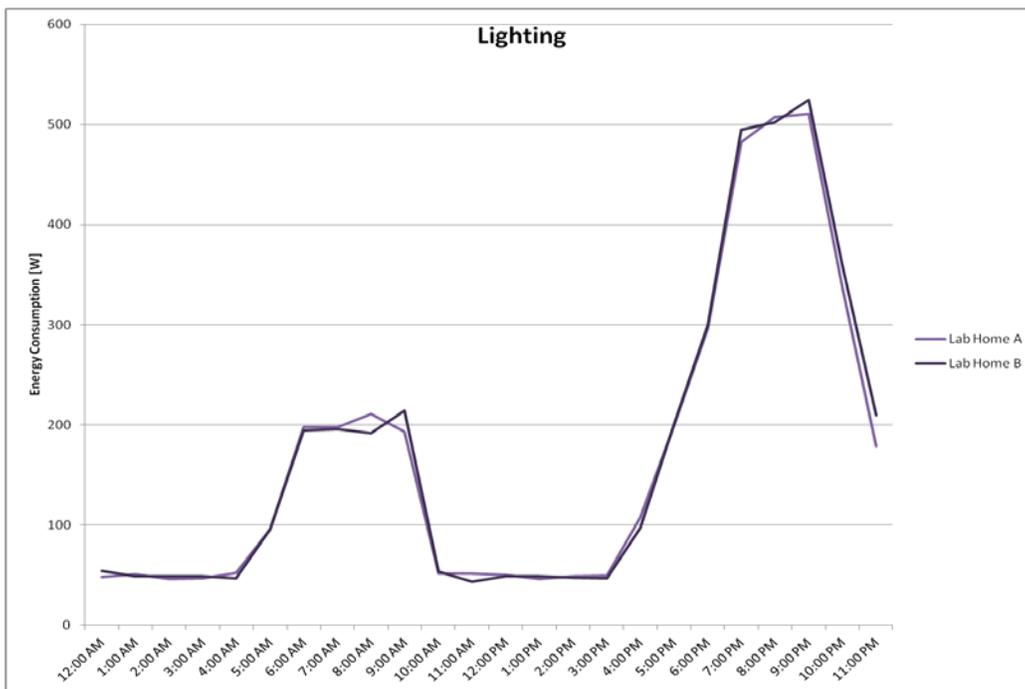


Figure B.2. Hourly Average Energy Consumption (W) Associated with Lighting for an Example Day during the Baseline Period

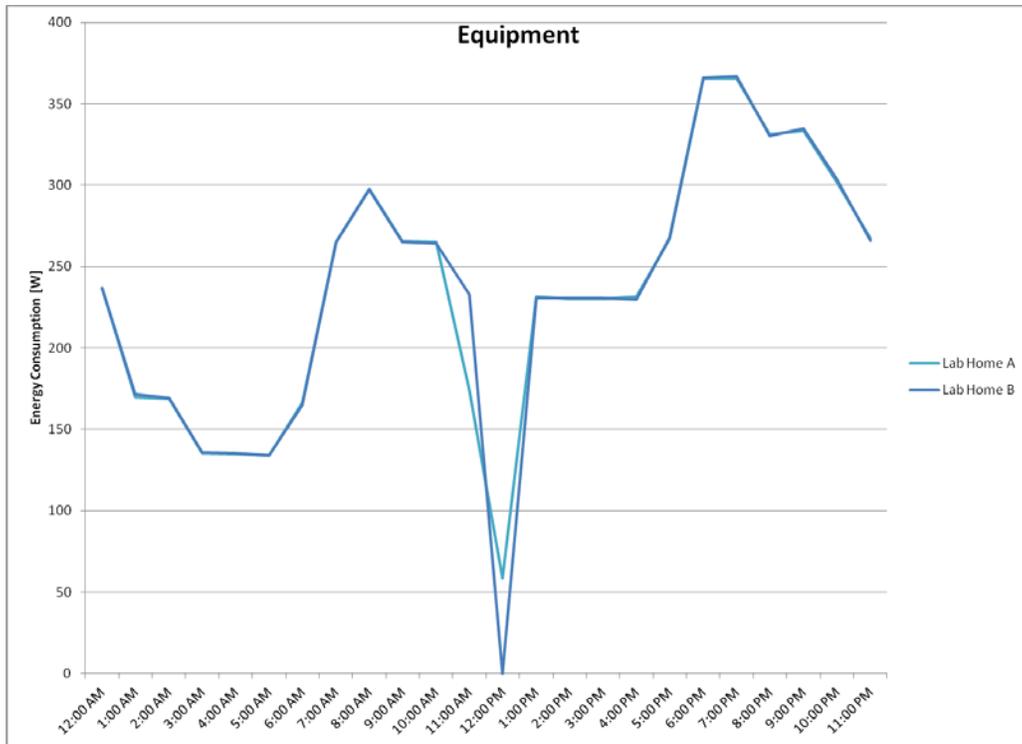


Figure B.3. Hourly Average Energy Consumption (W) Associated with Equipment Loads for an Example Day during the Baseline Period



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