PNNL-27663 Rev.1

Pacific Northwest
NATIONAL LABORATORY

Testing the Performance and Dynamic Control of Energy-Efficient Cellular Shades in the PNNL Lab Homes

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U.S. DEPARTMENT OF
ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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Pacific Northwest National Laboratory
Richland, Washington 99352

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[1] Efficiency Solutions, LLC, Richland, Washington

Summary

Heat transfer through windows accounts for a significant percentage of a building's energy use and adds substantially to the peak cooling load of a home. Window covering manufacturers currently offer high-efficiency insulated shades and motorized shading devices for certain product lines, but this automation is typically marketed as a convenience and security feature for the homeowner and often does not include energy-optimized control algorithms or dynamic and responsive features. This report describes the experimental design and results of testing the energy performance of Hunter Douglas double-cell cellular shades under various control schemes in the Pacific Northwest National Laboratory's (PNNL) Lab Homes. The results of both heating and cooling season experiments are presented. Tests were designed to assess the heating, ventilation, and air conditioning (HVAC) savings resulting from the thermal insulating properties as well as the automated and dynamic control strategies of shading devices. Control schemes tested included common "connected home" strategies where controls were integrated and coordinated between the window shading device, building thermostats, and external sensors.

Experiments were specifically designed to examine persistence of savings with dynamic and potentially automated operation. To examine energy use and savings potential under typical use operational settings, a typical use scenario was developed based on previous residential behavioral research sponsored by the U.S. Department of Energy (DOE). The report also includes results from testing designed to examine the benefits (in terms of comfort, energy savings, and responsiveness to control) of coordinating the operation of cellular shades with HVAC control as a demand-response measure. Testing was conducted during both the 2017 and 2018 cooling and heating seasons.

Some of the key findings for the cooling season are:

- High-efficiency cellular shades have significant energy-saving potential during the summer cooling season (25% HVAC savings), but this savings decreases considerably if the larger view windows of a home remain uncovered during the day, particularly if these are west- or south-facing windows.
- Cellular shades under typical use scenarios (i.e., some shades up and some shades down) do produce HVAC savings; however, when the high-heat-gain windows (i.e., large windows on west and south sides of a home) are left uncovered, the HVAC savings were only around 5%.
- In all cases and operational scenarios, double-cell cellular shades out-performed the typical vinyl Venetian blinds (6–15% average whole-home HVAC savings with cellular shades).
- With automated integrated controls, cellular shades could be coupled with thermostat setbacks to enhance residential demand-response programs and improve occupant comfort.

Some of the key findings for the heating season are:

- High-efficiency cellular shades have significant energy-saving potential during the winter heating season, but at least some of the larger south- and/or west-facing window shades have to be operated (e.g., up during the day and down at night) to fully realize these savings benefits.
- When high efficiency cellular shades are used in a typical use fashion (i.e., some shades up and some shades down) during the winter months, the average HVAC savings during the experimental period were insignificant relative to having no shades.
- Cellular shades out-performed the typical vinyl Venetian blinds under the typical use scenario (2% HVAC difference) as well as static (i.e., fully down) scenarios (9% whole-home HVAC difference).

- Relative to typical Venetian blinds with typical use settings, double-cell cellular shades operated under multiple control strategies (whether executed manually or through automation) provided consistent energy savings benefits (~5–9% HVAC savings).
- With automated integrated controls, cellular shades could be coupled with thermostat setbacks to enhance residential comfort and energy savings.
- Smart control algorithms can be employed to achieve year-round savings; however, seasonal schedules, whether implemented through automation or manually, also can achieve consistent savings during both heating and cooling seasons.

While approximately 80% of the 118 million U.S. residential housing units have some form of window covering, more than 80% of these installed window attachments are made up of relatively low-efficiency (e.g., vinyl blind) coverings (Bickel et al. 2013; DOE 2018; AERC 2017). There would therefore appear to be a large market opportunity to shift consumers from less efficient window attachment products toward higher efficiency products such as high-efficiency cellular shades. Also, considering that typical use of these operable window attachments yields much lower savings than a variety of optimizing operation schemes, this would suggest that whether through automation or through manual operation, there is a need in this sector for efficiency and utility programs to help consumers make informed product choices and to help educate and incentivize “smart” energy-efficient operation of window coverings to help consumers fully realize energy savings from high-efficiency window attachments.

Acknowledgments

The authors would like to thank Hunter Douglas, who donated the cellular shades and the PowerView Motorization controller for this experiment. In particular, the authors would like to thank Stacy Lambright and Steven Mullaly of Hunter Douglas for their review and providing technical assistance with PowerView operating system and analysis. We would also like to thank Robert Weber and Janice Petersen of Bonneville Power Administration, Rob Curry of the Northwest Energy Efficiency Alliance, and Ken Nichols for providing support and constructive feedback throughout the duration of this project. Finally, we would like to thank Rick Pratt, Andrew Hoffman, and Eric Wilcox Freeburg of Pacific Northwest National Laboratory who assisted with the development of the VOLTTRON code.

Acronyms and Abbreviations

ACH50	air changes per hour at 50 Pascals of depressurization with respect to the outside
AERC	Attachments Energy Rating Council
Btu	British thermal unit(s)
D&R	D&R International
DOE	U.S. Department of Energy
°F	degrees Fahrenheit
ft	foot (feet)
HD	Hunter Douglas
HDKR	Hay, Davies, Klucher and Reindl (model)
hr	hour(s)
HVAC	heating, ventilation, and air conditioning
kW	kilowatt(s)
kWh	kilowatt hour(s)
LBNL	Lawrence Berkeley National Laboratory
NEEA	Northwest Energy Efficiency Alliance
Pa	Pascal(s)
PNNL	Pacific Northwest National Laboratory
SHGC	solar heat gain coefficient
Wh	watt-hour(s)
W/m^2	watts per square meter
yr	year(s)

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1.0 Introduction

Heat transfer through windows accounts for a significant percentage of a building's energy use and adds substantially to the peak cooling load of a home. Window attachment manufacturers currently offer motorized shading devices for certain product lines, but this automation is typically marketed as a convenience and security feature for the homeowner and often does not include energy-optimized control algorithms or dynamic and responsive features. To examine the energy-saving potential of both insulating cellular shades and potential automation strategies, Pacific Northwest National Laboratory (PNNL) conducted a series of whole-home experiments in its PNNL Lab Homes, a matched pair of homes located on PNNL's campus in Richland, Washington. The results of both heating and cooling season experiments are presented in this report, where testing was designed to assess the heating, ventilation, and air conditioning (HVAC) savings resulting from the thermal insulating properties as well as the automated and dynamic control strategies of shading devices. Control schemes tested included common strategies in which controls were integrated and coordinated between the window shading device, building thermostats, and external sensors. This report also includes results from testing designed to examine the benefits (in terms of comfort, energy savings, and responsiveness to control) of coordinating the operation of cellular shades with HVAC control as a demand-response measure.

During the 2017–2018 heating and cooling season, dynamic control of the cellular shades were evaluated in the Lab Homes at PNNL. In the energy performance experiment, PNNL evaluated the performance of the Hunter Douglas (HD) Duette Architella Elan double-cell cellular shades installed in the experimental home (Lab Home B). Whole-home HVAC use for the experimental home, where the cellular shading technology was installed, was compared to the whole-home HVAC use in the baseline home (Lab Home A), which had horizontal slatted vinyl blinds installed over the windows. The blinds in the baseline home were operated in a manner that is "typical" for residential home based on a U.S. Department of Energy (DOE) behavioral study related to window attachment operation (D&R 2013). This study built off previous research and experiments that examined the HVAC energy savings potential of high-efficiency window attachment products and will expand the research of optimal control strategies.

Each home was identically operated to simulate occupancy (e.g., lighting, appliances, heating/cooling, etc.). Using HD operable cellular shades and modified automated controllers, second and third experiments were conducted to examine the effect of different operating schedules of attachments and coordination with HVAC grid-response events, respectively.

2.0 Background

There is a significant opportunity to improve the thermal envelope of today's homes by upgrading the performance of existing windows. In fact, DOE estimates that 42% (47.2 million) of U.S. homes have single-pane windows (DOE 2009), and based on DOE and industry shipment data, it has been estimated that an additional 46 million homes have double-pane windows with clear glass but not low-e glass (Cort 2013; DOE 2009). Complete window replacement can be expensive and occurs in only an estimated 2% of homes each year (AERC 2017). Given that approximately 80% of windows in U.S. homes have some sort of window attachment (e.g., blinds, shades), there is an opportunity to increase the performance of the existing window system by applying energy-efficient window attachments to these homes; however, limited detailed information exists that allows energy-efficiency programs and consumers to determine the energy savings potential for some of these window attachments. DOE and several utility organizations, including Bonneville Power Administration and the Northwest Energy Efficiency Alliance (NEEA), have launched testing programs and research efforts to study this issue.

Previous research funded by DOE and NEEA assessed the whole-home performance of the premium HD triple-cell cellular shades (Petersen et al. 2016). Selected results of the experiments are provided in Table 2.1. For all operating scenarios during the heating and cooling seasons, insulated cellular shades demonstrated significant energy savings when compared to vinyl horizontal slatted blinds, which are the most common window covering on the market and installed in U.S. residences. When using the HD Green schedule,[1] HVAC savings were approximately 15% in summer and 17% in the winter when compared to the control home with vinyl blinds operated in the same exact manner. Thus, the triple-cell cellular shades proved to be a more effective insulator in both seasons when compared to the vinyl blinds.

Table 2.1. Average HVAC Savings of the Triple-Cell Cellular Shades (Lab Homes testing during 2015–2016)

Experiment	Description	Season	HVAC savings
HD Green operation schedule compared to vinyl blinds	HD blinds operated per the HD Green schedule compared to standard vinyl blinds operated per HD Green schedule.	Cooling	15.3% ±2.9%
		Heating	16.6% ±5.3%
Static operation compared to vinyl blinds	HD 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%

Building from existing research, this report documents the findings from 2017–2018 experiments that were conducted with a less expensive double-cell cellular shade product to verify performance at a more accessible price point. In addition, the experiments are designed to help examine the impact of user operation on energy savings, including a scenario designed to reflect baseline conditions and energy use in the home when shades are used in a manner typical of most residential users.

One issue that has been raised with regard to the application of highly insulated operable window attachments is that the energy savings are dependent on the how the building occupant uses them. This is of particular concern to utility-sponsored efficiency programs, which must ensure persistence of savings for the technologies they promote as part of their programs. Operable window attachments give users the ability to use them as they see fit. This user control may or may not lead to energy savings, which can

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[1] The HD Green schedule is specifically designed to optimize HVAC operation and solar heat gain while allowing some daylighting to accommodate consumer needs for natural daylight.

sometimes be seen as a drawback from an energy-efficiency standpoint. However, the ability to operate window attachments can also provide a dynamic element to a standard window that extends beyond the insulating properties by operating them in a manner to allow solar gains when beneficial during the winter and reducing solar gains in the summer. To examine both the thermal insulation and dynamic features on whole-home energy performance, new Lab Home experiments were designed to address the following questions:

- How much do these high-efficiency products save if they are operated the way a typical residential occupant would operate them?
- How much does optimal operation play a role in the savings?
- Are high-efficiency shading devices good candidates for automated controls and/or “smart” automated controls and could they be easily integrated into a “smart” connected home system?

The experiments discussed in this report are conducted in partnership with the Bonneville Power Administration, DOE, NEEA, HD, and Efficiency Solutions. The experiments test the capabilities of the high-efficiency cellular shading devices and associated automated control strategies in the PNNL Lab Homes. The goal of these experiments was to determine the extent to which varied schedules impact the HVAC load, and develop control algorithms that take input signals from weather and thermostat data to dynamically adjust the cellular shade’s positions in response to these signals.

In 2015, the DOE sponsored the development of the Attachment Energy Rating Council[1] (AERC), which is a an independent, public interest, non-profit organization whose mission is to rate, label, and certify the energy performance of window attachments, such as cellular shades. The first products that will receive AERC ratings include interior and exterior storm windows, cellular shades, blinds, roller shades, solar screens, and pleated shades. Ratings will be available for additional product categories in 2019. The results of this study will directly contribute to the efforts of the AERC by providing additional performance data on the double-cell class of cellular shades, both in thermal performance comparisons and operational impacts on whole-house savings.

2.1 The Technology: Cellular Shades and Automation

Window attachments are interior and exterior products that are installed over windows or doors in residential and commercial buildings. Interior products often are referred to as window treatments or window fashions and include blinds, shades, drapes, shutters, window quilts, and films. Exterior products include roller shades, roller shutters, and awnings. Attachments also include both interior and exterior storm windows. Window attachment products, particularly interior ones, have traditionally been thought of as a decorative feature; however, these products offer a variety of benefits to homeowners, including energy savings. The flexibility offered by attachments allows end-users to choose products that fit their lifestyle and that can be adapted to meet hourly or seasonal needs. Automatically and manually controlled products provide additional options for customers and can offer increased savings depending on climate zone.

2.1.1 Insulating Cellular Shades

Within the interior window coverings category, honeycomb cellular shades typically have the highest R-values because of their layered or concentric designs. Introduced in the 1980s, cellular shades are designed to trap air inside pockets that act as insulators. This design can increase the R-value of the window covering and reduce the conduction of heat. Insulating shades can also impact solar heat gains if

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[1] See https://aercnet.org/ for more information.

managed properly. The insulating air pockets may include a layer of metallized Mylar, which minimizes radiant heat transfer, similar to the effect that a low-emissivity coating has on windows. The specific technology examined as part of this study was the HD Duette® Architella® Elan™ honeycomb fabric shades, which are made with four layers of fabric and three insulating air pockets (Figure 2.1). The inclusion of multiple insulating air pockets, minimizes heat transfer and increases the effective R-value of the fabric.

Figure 2.1. HD Duette Architella Elan Semi-Opaque Shades

2.1.2 Shade Automation

Along with the added insulating properties of the shades, the HD Elan series come with the option to automate the shades with a built-in motor system (Figure 2.2). The built-in automation features enables a user to optimally manage solar gains throughout the day and year. The automated feature allows blinds to be opened and closed using preprogrammed schedules. The scheduling can be optimized based on the solar calendar and geographical location to reduce the HVAC load while ensuring that adequate light and thermal comfort is achieved within the conditioned space. For example, during the heating season, the schedule can be operated to maximize the duration of visible light and solar heat gain to the space during the daylight hours. Of course, the automated controls also allow the shades to be controlled based on other home owner preferences, including privacy and security preferences.

Figure 2.2. HD PowerView Battery-Operated Motor (left, encased, top of shade) and Example Remote Control Devices (center), including Mobile Device Applications (right)

Currently available automated window attachments can be powered from batteries, electrical outlets (i.e., plug-in), or hard wiring. A battery-operated window attachment has the advantage of not needing electrical connection and does not require installation from an electrician, but is best suited for smaller or lighter window attachments. A plug-in window attachment control also does not require an electrician, but outlets and cords can be unsightly if not designed into the construction of the building. An outlet-powered window attachment controller typically uses a direct current motor and is best suited to power low- to medium-weight window attachments. Hard-wired systems are usually installed during construction and typically use stronger motors that are well suited for heavier window attachments or systems of multiple window attachments. There are several companies that offer window attachment controls or automation systems, including HD PowerView®, Lutron Caséta®, and Spring Fashion's Graber Virtual Cord® (Cort and Johnson 2017). The HD PowerView® Motorization system was used in the experiments described in this report.

2.1.3 Integrating Platform

The VOLTTRON[1] open-source distributed control and sensing platform, developed by PNNL, was used to control cellular shades for selected experiments. VOLTTRON is designed specifically to facilitate communication and device control between many different technologies. It is a non-web based platform that provides a secure infrastructure so it is not susceptible to cyber-attack and can be easily expanded. These experiments expand on some of the previously tested capabilities of VOLTTRON (e.g., controlling electric vehicle charging stations and commercial building control systems) to serve as the integrating application platform for selected residential shading experiments. Because of its ease of communicating with multiple devices at high speeds, VOLTTRON works well with utility applications in addition to integrating sensing and controls within the home. Although its capability is not the focus of these experiments, VOLTTRON is an acceptable platform for utility demand-response programs. If successful, these experiments could provide further validation that shading automation and control could be integrated into a multi-sided platform capable of receiving and responding to external signals, and, thus, provide "proof of this concept" for integrating automated shading into demand-response programs.

2.2 Window Attachment Energy Savings and Previous Research

In 2013, 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 the focused on user behavior with respect to operable window coverings (Bickel, Phan-Gruber, and Christie 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. In addition to DOE's research focused on window coverings, a number of research institutions, energy-efficiency programs, and utilities have completed characterization and meta-analyses (Ariosto and Memari 2013) and energy simulation analyses (Zirnhelt et al. 2015; Metzger et al. 2017) validating energy savings from cellular shades and other window attachments in multiple climate zones and prototype residential buildings. Table 2.2 provides a summary of modeling simulation research that has been conducted related to cellular shades.

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[1] VOLTTRON is an open source interoperable reference platform that supports a wide range of applications such as managing energy end-use loads, increasing building efficiency, etc. For more information, go to the VOLTRON website at http://transactionalnetwork.pnnl.gov/volttron.stm.

Table 2.2. Summarized Case Studies Focused on Window Attachments and Cellular Shades

Study	Sponsor	Baseline description	Findings
LBNL Modeled Estimates (Curcija et al. 2013)	DOE	Five product types over single-pane and double-pane windows in 12 climate zones	Modeled energy savings varied by product types, climate zone, and baseline, but annual energy dollar savings ranged from \$280 to \$470 for cellular shades.
Energy Savings from Window Shades (Zirnhelt, Bridgeland, and Keuhn 2015)	HD and Rocky Mountain Institute	EnergyPlus modeling of DOE residential buildings	Modeling of cellular shades showed: Denver maximum cooling savings – 25% Denver maximum heating savings – 10% Peak electrical demand reduction of 9% for new homes
Evaluation of Residential Window Retrofit Solutions (Ariosto and Memari 2013)	Pennsylvania Housing Research Center	Modeled cellular shades	Reduction in U-factor of 38%
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	Modeled reduction in U-factor of 15% Actual increase in R-value of 60%
Modeling Cellular Shades in Multiple Climate Zones (Metzger et al. 2017)	PNNL	Energy Plus simulated energy models in multiple prototype homes in 13 climate zones.	Annual HVAC savings ranged from 10% to 34% when compared to homes with no shading. Shades operated in down position during cooling season and lowered during the evening during the heating season.

There has been only limited research examining residential energy savings from shading devices and dynamic control strategies. LBNL has conducted research on highly insulating residential “smart” automated shades with Pella’s between-the-glass motorized shading systems, using its MoWITT test facility. However, most of the “smart” shading research to date has focused on solutions for commercial buildings, including research on electrochromic glass (Hart and Selkowitz 2015; Lee et al. 2006).

3.0 Experimental Platform and Design

The evaluation of window attachments took place in the PNNL Lab Homes between May 2017 and March 2018. This section describes the Lab Homes facility, the experimental timeline, window attachments used in the experiment, and data collection and analysis methodologies. Detailed experimental design configurations, including electrical, temperature, and environmental points monitored, daily occupancy and lighting schedules and simulated loads are found in the *Experimental Plan* report (Cort et al. 2017) and summarized in Appendix A.

3.1 Lab Homes

The experiments were conducted in PNNL's side-by-side Lab Homes, which are platforms for precisely evaluating energy-saving and grid-responsive technologies in a controlled environment. The PNNL Lab Homes are two factory-built homes located on PNNL's campus in Richland, Washington. The floor plan of the homes is shown in Figure 3.1.

These 1500 sq. ft. homes have three bedrooms and two bathrooms. The insulation levels include R-22 floors, R-11 walls, and R-22 ceilings. The homes are fully equipped with laboratory-level monitoring equipment, circuit-level controls, and three types of heating systems (Cadet wall heaters, electric forced-air furnaces, and 7.7 Heating Seasonal Performance Factor heat pumps.

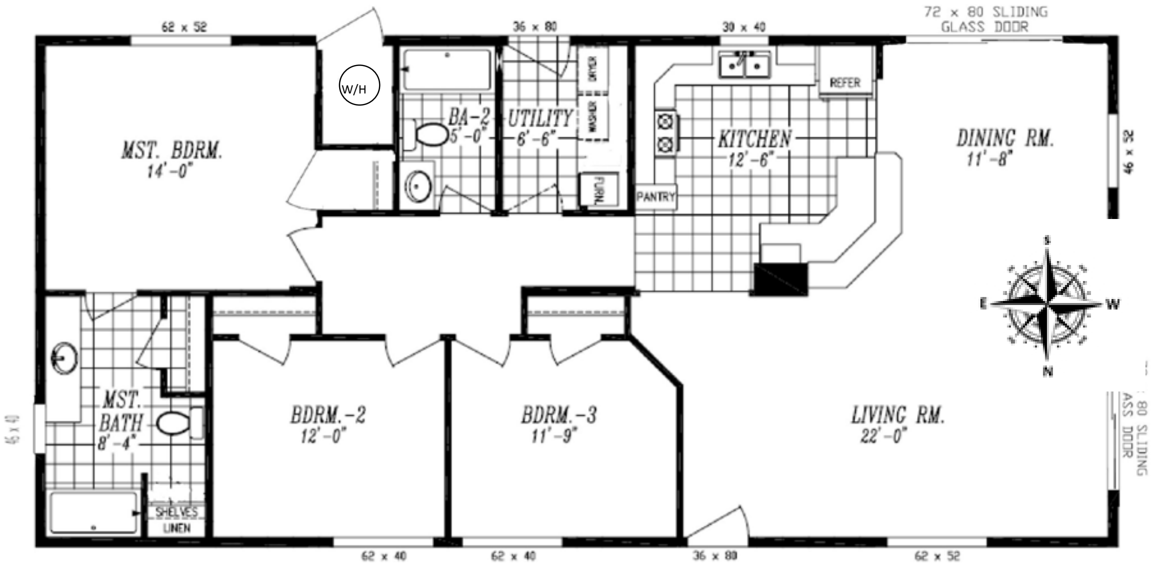

Figure 3.1. Floor Plan of the Lab Homes as Constructed

Each Lab Home has seven windows and two sliding glass doors, for a total of 196 ft^2 of window area. The control home was equipped with horizontal slatted vinyl blinds and the experimental home was equipped with wi-fi connected cellular shades. For the primary experiments, the "experimental home" was retrofitted with HD honeycomb shades[1], while a matching "baseline home" was equipped with typical vinyl blinds[2] or no window coverings, depending on the experiment.

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[1] HD Duette Elan double-cell honeycomb shades, semi-opaque white fabric (C23).

[2] "Typical blinds are horizontal white slatted vinyl blinds with 1-inch slats.

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-framed sliders. For the experiment, window attachments were installed over the experimental home’s windows and sliding glass doors, with the exception that the frosted glass master bathroom windows were left uncovered in both homes. HD cellular shades were installed on the interior side of the primary windows. The number and dimensions of the windows were as follows:

- Two each 62- × 52-inch two-track sliders
- Two each 62- × 40-inch two-track sliders
- One each 30- × 40-inch two-track sliders
- One each 46- × 52-inch two-track sliders
- Two each 72- × 80-inch 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 inches. Equipped with a battery pack and small motor, the shades could be automatically raised and lowered using pre-programmed schedules or from commands from VOLTTRON or researchers. The shades were controllable through the VOLTTRON connection that also controls the thermostat. Alternatively, the thermostat can be controlled by a built-in scheduling application. An HD network was used to communicate to individual or groups of shades within the system. Wireless signals were sent via the network to specified window coverings to open and close based on predefined schedules or commands. Because of 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 provides photos of the Duette Elan cellular shades used in the experiments, where the semi-opaque fabric allowed filtered natural light to enter the space even when fully deployed (e.g., pulled down).

Figure 3.2. Semi-Opaque Double-Cell Shade Pulled Down (left) Allows Filtered Natural Light into North-Side Bedroom. Close-up view of same shade (right).

3.2.1 Window Attachment Performance Ratings

The U-factor and solar heat gain coefficient (SHGC) for the primary windows are listed in Table 3.1. Installing a shade behind a primary window will alter the SHGC, U-factor, and visible transmittance. When fully closed, typical vinyl blinds are expected to decrease the U-factor of the window opening by approximately 0.07–0.13 Btu/hr-ft^2-°F (Curcija et al. 2013) and depending on the blind, greatly reduce the SHGC and visible transmittance, which should decrease the observed energy use in both homes.

Table 3.1. Primary Window Characteristics

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

Although the National Fenestration Rating Council provides U-factor ratings for primary windows, it does not provide equivalent rating for window attachments. To address this gap, the AERC[1] was formed in 2015 with the support of the DOE 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. The AERC has developed the Complex Glazing Database[2] to store thermal and optimal performance information about materials used in window attachments as well as the geometry of window attachment products. Although currently under development, it is slated to provide publicly available and searchable electronic data related to window attachment product performance by the end 2018.

3.2.2 Typical Use Shade Positions

To examine the reasonably achievable energy savings benefits of various operation settings, baseline conditions that reflect how shades and blinds perform under "normal" or "typical" household settings were developed. The typical use shading position settings of residential building occupants were developed based on the results of a 2013 behavioral study conducted by D&R International (D&R). Three key findings from the D&R study are reflected in the typical use scenario. These findings include:

1. People rarely move or adjust their window coverings in a home throughout the day.
2. People tend to keep their window coverings closed in areas where they would like privacy (e.g., windows and bathrooms) and open in common areas that have views (typically living rooms and dining rooms).
3. There is some variation in the position of the window coverings that appears to be based on climate/weather (e.g., warmer climates kept more window coverings closed in the summer months).

Based on findings from the D&R study, typical use for our experiments was reflected by slight variations in the positions of shades/blinds throughout the home where the bedroom and bathroom attachments were kept in a the closed position, and attachments in common areas and view areas (e.g., living room, dining room, and kitchen) were kept open. To reflect the finding that people rarely move the window coverings, the position of attachments under the typical use scenario did not change throughout the day. To reflect

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

[2] https://aercnet.org/certification/complex-glazing-database/

the slight variation in positions based on climate/weather, attachments on the west-facing windows in the living room and dining room were kept halfway closed during the cooling season to avoid excessive heat gain and glare in the afternoons. The typical use settings were kept the same for both the summer and winter experiments.

Figure 3.3 illustrates the configuration of a Lab Home and identifies the position of the shades/blinds under the typical use scenario. As previously mentioned, it is assumed that most residential consumers have their blinds drawn in areas where they most desire privacy. This would be the bedroom and bathrooms, which are located on the east side of the Lab Homes and are shown to have blue rectangle covering them in Figure 3.3. The red rectangles show window area that remained half open for the full duration of the experiment. Because solar gains in the summer are most readily noticed by the building occupant on the west side of the building, window coverings were drawn partway down over the west-facing windows. The remainder of the coverings windows in the common areas (west side of house) remained fully drawn in an open position. In both homes, the master bathrooms have small windows that have privacy (frosted) glass; therefore, neither have window coverings.

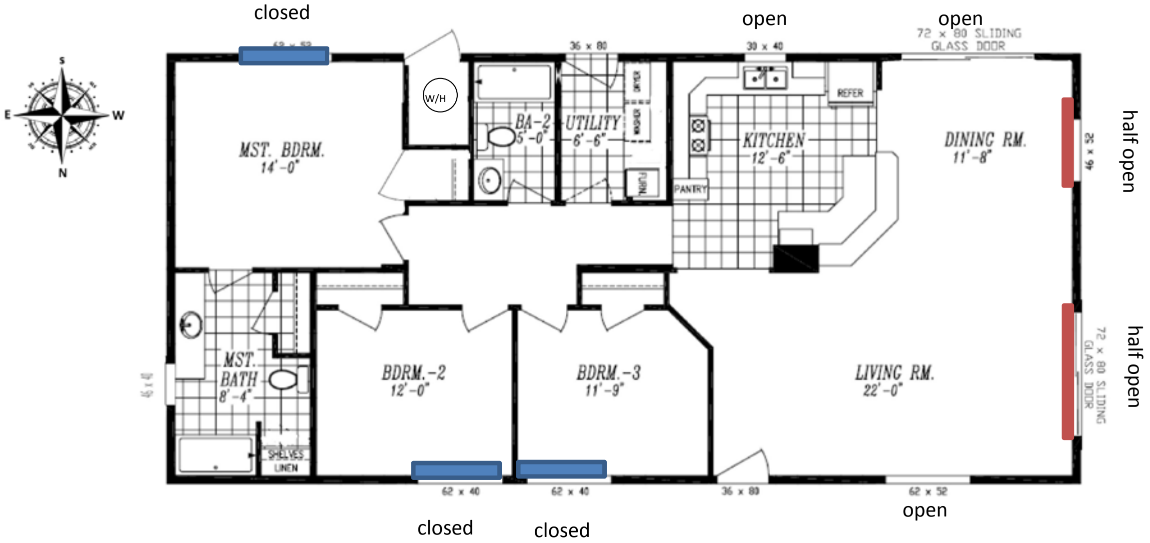

Figure 3.3. Lab Homes Floor Plan with Typical Use Operational Settings Indicated with Blue and Red Lines. Blue indicates closed window shades and red indicates half-opened window shades.

3.3 Experimental Design, Timeline, and Operational Settings

The following research questions are answered by this Experimental Plan:

1. What is the whole-home energy savings potential from the installation of double-cell cellular shades[1] installed over double-pane, clear-glass windows when compared to the following scenarios:
    - A home with no window coverings
    - A home with the vinyl horizontal blinds (the most ubiquitous window covering on the market).

    These savings were examined under two operating scenarios: 1) shades/blinds always closed and 2) shades/blinds operated in a manner that is typical of residential homes where typical use is based on the results of the DOE-sponsored behavioral study (D&R 2013) (described in Section 3.2.2 of this report).

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[1] HD Duette Architella Elan

2. What is the impact of operation and optimal control schemes on the energy savings of the double-cell cellular shade when compared to a home with standard window coverings (i.e., vinyl horizontal blinds) that are operated in a typical fashion (as defined in Section 3.2.2 of this report)?
3. What are some enhanced automation and dynamic features that can aid in energy savings? What is the difference in energy savings of cellular shades that are dynamically controlled through a thermostat, external weather data, or other local indoor temperature compared to vinyl horizontal blinds that are operated in a typical fashion? Can the control scheme be optimized based on external parameters and the cardinal direction of windows during key points of the day?
4. Can dynamically controlled shades be used as grid-responsive devices?
5. If integrated with HVAC conservation, could the shades help improve energy savings and/or comfort to the building occupant?

The energy savings potential was quantified both in the heating season using the electric resistance forced-air furnace in both homes, and during the cooling season using the SEER 13, 2.5-ton split-system heat pump.

3.3.1 Lab Home Commissioning

To verify that both the homes were operated in the same manner, a baselining experiment was conducted where both homes were monitored without any window attachments and the same simulated occupancy use and settings. Theoretically the two homes should have the exact same readings, which would be ideal for testing the impact of retrofit measures. This experiment was completed before the cooling experiments began (May 2017) and was repeated toward the end of the experimental period to verify that the homes were both still in calibration with one another. To conduct the commissioning exercise, the thermostat setpoints were set at the same temperature. Windows were left uncovered in both homes while energy consumption at several monitoring points was observed over multiple days. Results from the baseline commissioning testing for the cooling season showed that the two homes consume nearly the same amount of energy with only a 0.26% difference between them.

The commissioning was repeated with the HVAC set to heating mode in preparation for the heating experiments (October 2017). During the heating experiments, one of the Lab Homes experienced a data logger signal-output failure, which required resetting the data logger and repeating commissioning experiments. Also during the heating season, one of the home’s experienced issues with the thermostat drifting from the setpoint, which also required resetting and repeating commissioning experiments. To minimize the resources required and the possible error associated with simulated loads, no lighting, equipment, or occupancy was simulated in that experiment. Based on these commissioning experiments, an appropriate correction factor or offset was embedded in the resulting performance data to reflect the baseline HVAC consumption differences between the two homes. All data that was identified as being biased with thermostat drift or other equipment issues were removed from sample testing results and corresponding statistics.

Further detail on commissioning results can be found in Appendix B of this report.

3.3.2 Experiment

For most experiments, the thermostat setpoint during the cooling season was set to 76°F with no setback, and the thermostat was set to 71°F during the heating season with no setback. The setpoint was chosen based on the 2014 Building America House Simulation Protocols (Wilson et al. 2014). Certain experiments did use a thermostat setback, and those are described where relevant in the sections below.

3.3.2.1 Thermal Performance of Cellular Shades

The purpose of this initial static testing was to understand the efficiency of the double-cell shade compared to a home with no window coverings as well as to the baseline home with vinyl horizontal blinds. Vinyl horizontal blinds were selected for use in the baseline home because this class of window covering makes up over 80% of the residential market (AERC 2017). The thermostat setpoint during the cooling season was set to 76°F with no setback, and the thermostat was set to 71°F during the heating season with no routine setbacks. The setpoint was chosen to generate a large temperature differential between indoors and outdoors to maximize the observed HVAC impacts while keeping the setpoints in a range representative of real home occupancy conditions.

Static Experiment -- Cellular shade performance compared to no window attachments

This experiment isolated the energy savings associated with the cellular shades compared to a building envelope without any fenestration products. The experimental home had double-cell cellular shades that remained closed for the full duration of the experimental period. The baseline home did not have any window coverings. The HVAC energy use was compared between the two homes. This experiment was identical in operation during both the heating and cooling seasons.

Static Experiment – Cellular shade performance compared to vinyl blinds performance

This experiment isolated the energy savings associated with the cellular shades compared to vinyl horizontal blinds. The experimental home had double-cell cellular shades that remained closed for the full duration of the experimental period. The baseline home had vinyl horizontal blinds that remained closed for the full duration of the experimental period. The HVAC energy use was compared between the two homes.

Typical Use Comparison Experiment

Using the typical use positions described in Section 3.2.2, the baseline home used vinyl blinds, while the experimental home had cellular shades. Both Lab Homes had identical setpoints and HVAC equipment. Experimental energy savings were scaled by the experimental offset determined during the system commissioning described in Section 3.3.1. This experiment was identical in operation between both the heating and cooling seasons.

3.3.2.2 Testing of Optimal and Integrated Control Features and Demand Response

Each Lab Home was equipped with a VENSTAR T7580 smart thermostat. These wi-fi enabled thermostats communicated with the VOLTTRON platform and HD PowerView automated shade controller. This set of experiments evaluated the energy use under varied control schemes in the experimental home while maintaining a typical use operation scenario in the baseline home. The varied control schemes included the integration of thermostat setbacks in coordination with cellular shade operation. It also examined the impact of typical control schemes such as occupancy controls that override the control schemes with seasonally optimal adjustments when no occupants are present in the home. The baseline home vinyl horizontal blind settings were operated in a manner that corresponded with the typical use scenario as described in Section 3.2.2 of this report.

Optimal Shading Control: HD Green Mode

With this experiment, we observed the impact of optimal operation on energy use as compared to a home with typical use settings (see Section 3.2.2). To capture the "optimal operation," we employed the HD Green Mode Schedule[1] in the common living areas of the home (e.g., living room, dining room, and kitchen) while keeping the blinds closed in the bedrooms and bathrooms (which corresponds with typical use for those areas). The baseline home was equipped with vinyl horizontal blinds in typical use positions. See Appendix C of this report for the specific schedule employed by HD Green Mode.

Typical Use with Occupancy Sensor Override (Cooling Season)

From an energy-efficiency perspective, an optimal shading control scheme during the summer cooling season would have the shades remain in the closed position throughout the day. This, however, is not a reasonable control scheme for an occupant who would like to look out the windows. Thus, summer season optimal control schedules and strategies, such as the HD Green Mode, will attempt to optimize energy use based on the orientation of the window and angle of the sun while allowing views and daylighting through the window during periods of the day. If the home occupant is not present, however, views and daylighting are not needed; thus, energy savings could be realized from integrating an occupancy sensing override that closes all window shades when nobody is home during the day during hot summer months. To evaluate the energy use under this control scheme, the experimental home was operated in a typical use manner, but included a simulated occupancy control override, where no occupants are assumed present in the home during working hours (from 9AM to 5PM). At 5PM, typical use resumes in experimental home for all common area rooms. In the baseline home, the typical use scenario is assumed with vinyl horizontal blinds covering all windows throughout the day and night.

Best Practices (Heating Season)

From an energy-efficiency perspective, an optimal shading control scheme during the winter heating season would have the shades remain in a closed position during the evenings and early morning when the sun is down, but shades would open during the day to allow beneficial heat gains into the home. To keep things simple, this experiment was designed so shades are raised during day starting at 6 AM, and then closed at 6 PM. Although this might not perfectly align with the daylighting benefits from opening different windows at different times or the insulating benefits from closing the shades exactly when the sun goes down, it was a simple strategy that could either be deployed manually or through a programmed schedule. Two separate experiments were performed. For Part I, only shades in the common living areas (i.e., living room, dining room, and kitchen) are opened and closed during the day, while the remaining window coverings remain in the typical use mode (where shades are pulled down in the bedrooms). In Part II, all window coverings, including the bedroom areas were opened and closed to examine the difference in performance from partially operating shades versus full operation of shades. This experiment also was run with some thermostat setbacks to examine both the sensitivity of incremental savings to thermostat setbacks, and the difference in comfort effects during setback periods.

Demand Response (Cooling Season)

We examined the impact of combining a thermostat setback conservation measure with strategic control of the cellular shades. We observed the impact on HVAC energy use reduction both in terms of magnitude of energy saved and the response to the "event" that triggers the thermostat setbacks and cellular shade closure. We also observed the impacts on comfort in terms of the mean temperatures

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[1] Developed by HD, 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. A detailed description of the schedule of operation is found in Appendix C.

observed throughout the home. This experiment was conducted in two parts. In Part I, the full impact of strategically closing the cellular shades in coordination with a 4°F thermostat set-up during a 4-hour peak period was compared to baseline control home with typical vinyl blinds and no set-up. Part II of the experiment l added a thermostat set-up in the baseline control home so the only differences between the two homes were the different shade materials and deployments (i.e., closing) of cellular shades during the peak period.

"Smart" Dynamic Operation

This experiment allowed for heat transfer through the envelope to be optimized depending on the season, weather, and time of day. During this period, the baseline home had vinyl horizontal shades operated in the typical fashion. A control algorithm was developed by PNNL to control HD cellular shades in the Lab Homes via VOLTTRON (see Appendix D of this report). The algorithm estimated the total heat flux (W/m^2) into or out of the window, both when it is uncovered and when it is covered by the cellular shades at the current time. The estimated heat flux was based on:

- The thermal properties of the window and shades, coupled with the interior and exterior temperatures.
- The optical properties of the window and shades, coupled with the estimated incident solar radiation on the exterior of the window. The incident solar radiation was estimated based on solar angle calculations and the assumed impact of local cloud cover on attenuating clear sky solar radiation.

Next, the algorithm decided on a preference for the window to provide either heating or cooling to the space. This preference is a function of the space temperature, the thermostat setpoint temperature, the thermostat heating or cooling mode, plus some strategic (preheating or pre-cooling) preference based on the time of day and the forecasted high or low temperature.

With the preference for heating or cooling established, the control action (shades up or down) was determined based on the estimated heat fluxes of the two control options. A preference for cooling would lead to the control option that provided the lowest heat flux into the house (or highest heat flux out of the house), and vice versa.

This control strategy was implemented for demonstration purposes and was based purely on optimizing the energy performance of the window system. Other practical considerations like views, privacy preferences, and daylighting were not taken into accounted. The HVAC thermostat was set in the cooling (76°F) or heating (71°F) mode depending on the season.

3.3.3 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 April 2017. Cooling season data was collected from May through September 2017, and heating season data was collected from October 2017 through March 2018. During both the heating and cooling seasons, the impacts of the cellular shades on the HVAC systems were compared during differing operational modes and to other window attachments, which are listed in Table 3.2 and Table 3.3, and described in further detail in Section 3.3.2 of this report.

The interior blinds in the baseline home were typical white vinyl horizontal blinds over the windows and vertically hung slat blinds over the sliding glass doors.

Table 3.2. Experimental Timeline for Cooling Experiments (May 2017–September 2017)

Cooling Testing Commissioning and Experiments	Duration	Date
Commissioning and Thermal Performance Testing Period		
Lab Homes Commissioning Period	29 days	5/01-5/29/2017
Lab Homes Baseline	13 days	5/30-6/11/2017
Static Use – Cellular shades down compared to no shades	11 days	6/12-6/22/2017
Static Use – Cellular shades versus vinyl shades in down position	6 days	6/23-6/28/2017
Typical Use Comparison – Cellular shades versus vinyl in typical use mode	8 days	6/29-7/06/2017
Typical Use in experimental Home Compared to No Use in Baseline Home	7 days	7/07-7/13/2017
Optimal and Integrated Control Strategies		
Optimal Control – HD Green Mode	6 days	7/14 – 7/19/2017
Typical Use with Occupancy Override 9AM-5PM	11 days	7/20 – 7/30/2017
Integrated Control and Demand Response	25 days	7/31 – 8/24/2017
Part 1: Typical Use in Experimental Home 4°F Setback 3pm-7pm, Typical Use in Baseline Home	16 days	7/31-8/15/2017
Part 2: Typical Use in Experimental Home and Baseline Home 4°F Setback 3pm-7pm Both	9 days	8/16-8/24/2017
Commissioning period		
Second Baseline Check – No windows attachments – all up	7 days	8/25-8/31/2017
Verification of Previous Experiments		
Run 2 - Static Operation in Experimental Home Down; Baseline Home Up	2 days	9/13-9/14/2017
Run 2 - Static Operation in Experimental Home Down; Baseline Home Up	6 days	9/15-9/20/2017
Run 3 - Static Operation in Experimental Home Down; Baseline Home Up	7 days	9/21-9/27/2017
Typical Use in Baseline Home Compared to No Use in Experimental Home	7 days	9/28-10/04/2017
Typical Use in Experimental Home Compared to No Use in Baseline Home	7 days	10/05-10/12/2017

Table 3.3. Experimental Timeline for Heating Experiments (October 2017-April 2018)

Heating Test Commissioning and Experiments	**Duration**	**Date**
Commissioning and Thermal Performance Testing Period		
Winter Baseline – 1	25 days	10/31/2017-11/26/2017
Static Use – Cellular shades versus vinyl shades in down position	5 days	11/27/2017-12/03/2017
Static Use – Cellular shades down compared to no shades	6 days	12/04/2017-12/12/2017
Typical in Experimental Home Compared to No Use in Baseline Home	8 days	12/14/2017-12/26/2017
Typical Use Comparison – Cellular shades versus vinyl, typical use	7 days	12/27/2017-01/03/2018
Winter Baseline – 2	10 days	1/9/2018-1/17/2018
Optimal and Integrated Control Strategies (Control Home operated with vinyl shades in typical use mode)		
Optimal Control – HD Green Mode	6 days	01/19/2017-01/25/2018
Best Practices **Part 1**: Shades open common area: 6AM to 6PM. Shades closed: 6PM to 6AM. Typical use in baseline home.	8 days	01/26/2018-02/04/2018
Best Practices **Part 2**: Shades open common area 6AM to 6PM with 5°F temperature setback from 9PM-6AM in both homes. Typical use in baseline.	2 days	02/05/2018-02/07/2018
Best Practices **Part 3**: Shades open in all rooms: 6AM to 6PM. Shades closed: 6PM to 6AM. Typical use in baseline home.	3 days	02/12/2018-02/15/2018
Repeated Experiments		
Static Use – Cellular shades down compared to no shades	6 days	02/21/2018-02/25/2018
Winter Baseline -- 3	7 days	02/26/2018-03/05/2018
Typical in Experimental Home Compared to No Use in Baseline Home	6 days	03/06/2018-03/13/2018
“Smart” Dynamic Control and Testing		
Enhanced Control Features – WeatherUnderground application testing and Shoulder Season Testing of Enhanced Control Features	24 days	03/15/2018-04/08/2018

4.0 Results and Discussion

This chapter provides a summary of the comparison of the energy usage of the experimental home equipped with double-pane, clear-glass windows with interior cellular shades and the baseline home equipped with double-pane, clear-glass windows and either no attachments or typical horizontal vinyl blinds. Note that all experimental results are presented, in general, 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 was 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 Lab Home Commissioning Performance

Before experiments were conducted, the Lab Homes underwent a series of baseline measurements to verify the whole-house energy performance of for each home with the settings and seasonal conditions under which the experiments were performed.

4.1.1 Cooling Season Baseline Performance

As described in Section 3.3.1, the baseline for the cooling, summer season was completed with the windows left uncovered (i.e., no shades or blinds) in both homes. During the cooling season, the thermostats were set to 76°F, and two baseline tests were completed for quality assurance purposes.

The first cooling season test was conducted from May 30, 2017, through June 11, 2017, for a total of 13 testing days. This data showed an HVAC energy use difference of –0.89% ±2.49% with an average outdoor air temperature of 67°F. More energy was used in the experimental home than the baseline home.

The second series of baseline tests were conducted from August 26, 2017 through August 30, 2017 for a total of five consistent weather testing days. The results were consistent with the first test, resulting in an HVAC difference[1] of 0.35% ±2.36% with an average outdoor air temperature of 67°F. During this set of experiments, the outdoor environmental conditions were dominated with smoke haze and inversion conditions from regional wildfires. The smoke conditions are seen in an image from the PNNL main campus on September 5, 2017, Figure 4.1. Although the inversion produced extended warm periods into the evening hours, which were reflected in the data, the smoky conditions did not affect the home-to-home performance comparison.

A summary of baseline results is shown in Table 4.1.

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[1] Where the difference calculated is Lab Home A average HVAC use minus Lab Home B average HVAC use.

Figure 4.1. PNNL Main Campus Smoke – September 5, 2017

Table 4.1. Overall Baseline Performance Results

Summer Cooling Season - Baseline Performance

Date	Experiment	Savings	95% C.I.	Average T outside	Days
5/30 – 6/11/2017	Baseline #1	–0.87%	2.49%	67 F	13
8/26 – 8/30/2017	Baseline #2	0.35%	2.36%	67 F	5
	Baseline Averaged Savings (Correction Factor)	–0.26%	2.42%	67 F	9

Winter Heating Season - Baseline Performance

Date	Experiment	Savings	95% C.I.	Average T outside	Days
11/22-11/26/2017	Baseline # 1	3.49%	0.76%	46 F	5
1/9-1/17/2018	Baseline # 2	3.68%	1.90%	39 F	5
2/26-3/5/2018	Baseline # 3	1.16%	0.64%	41 F	7
	Baseline Averaged Savings (Correction Factor)	2.78%	1.10%	45 F	6

4.1.2 Heating Season Baseline Performance

The baseline for the heating season, was completed with the windows left uncovered (i.e., no shades or blinds) in both homes. During the heating season, the thermostat was set to 71°F. Repeated baseline tests were required during the heating season testing to identify and repair equipment issues in the homes. All data that was biased from known equipment issues and errors were eliminated from the data sample.

The first baseline experiment was conducted from November 22–26, 2017, for a total of five testing days. This data showed an HVAC energy use difference of 3.49% ±0.76% with an average outdoor air temperature of 46°F. More energy was used in the baseline home than the experimental home.

After performing a blower door test on November 6, 2017 (see Section 4.2), additional weatherization measures and data analysis were performed to try to identify the source of differences in HVAC energy performance between the two homes (Figure 4.2). Power spikes and inconsistencies between the two homes (Figure 4.2), led to further troubleshooting, which identified issues with the HVAC data logging system.[1] This issue was repaired and further testing was performed.

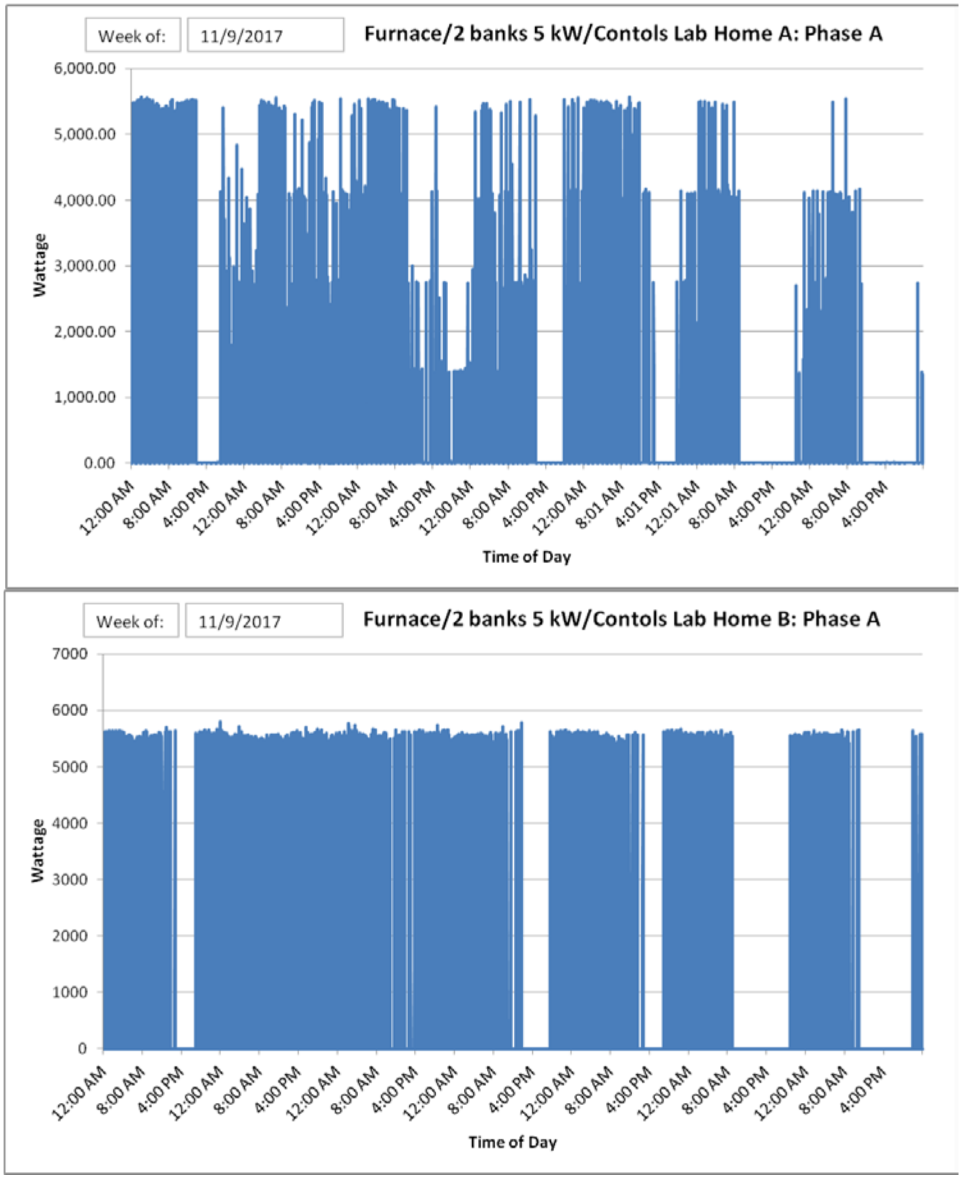

Figure 4.2. HVAC Furnace Heating Element Comparison: The Baseline Home (top) and Experimental Home (bottom)

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[1] A bad relay was providing incorrect voltage measurements from a current transformer.

A second series of baseline testing was conducted from January 9–17, 2018, for a total of five consistent weather days. This testing resulted in a difference in HVAC energy usage of 3.68% ±1.90% with an average outdoor air temperature of 39°F; however, further data analysis indicated that the thermostat in the experimental home was drifting from the setpoint of 71°F. Because of this issue, the thermostats were then soft reset every 7 days to ensure their setpoints were maintained, and test periods where setpoint drift was identified were discarded from the experimental data set.

A third series of baseline testing was performed starting on February 26, 2018, through March 5, 2018, totaling 7 days of consistent data. The difference in HVAC energy usage was 1.16% ±1 0.64% with an average outdoor air temperature of 41°F. An averaged value of these three baseline tests was estimated to be 2.78% ±1.10%, which was used to offset energy use differences between the homes for all winter experiments. Figure 4.3 shows the whole-house energy consumption on March 2, 2018, during the third series of baseline testing. The HVAC difference on this day was only –0.4% with the experimental home using slightly more energy than the baseline home.

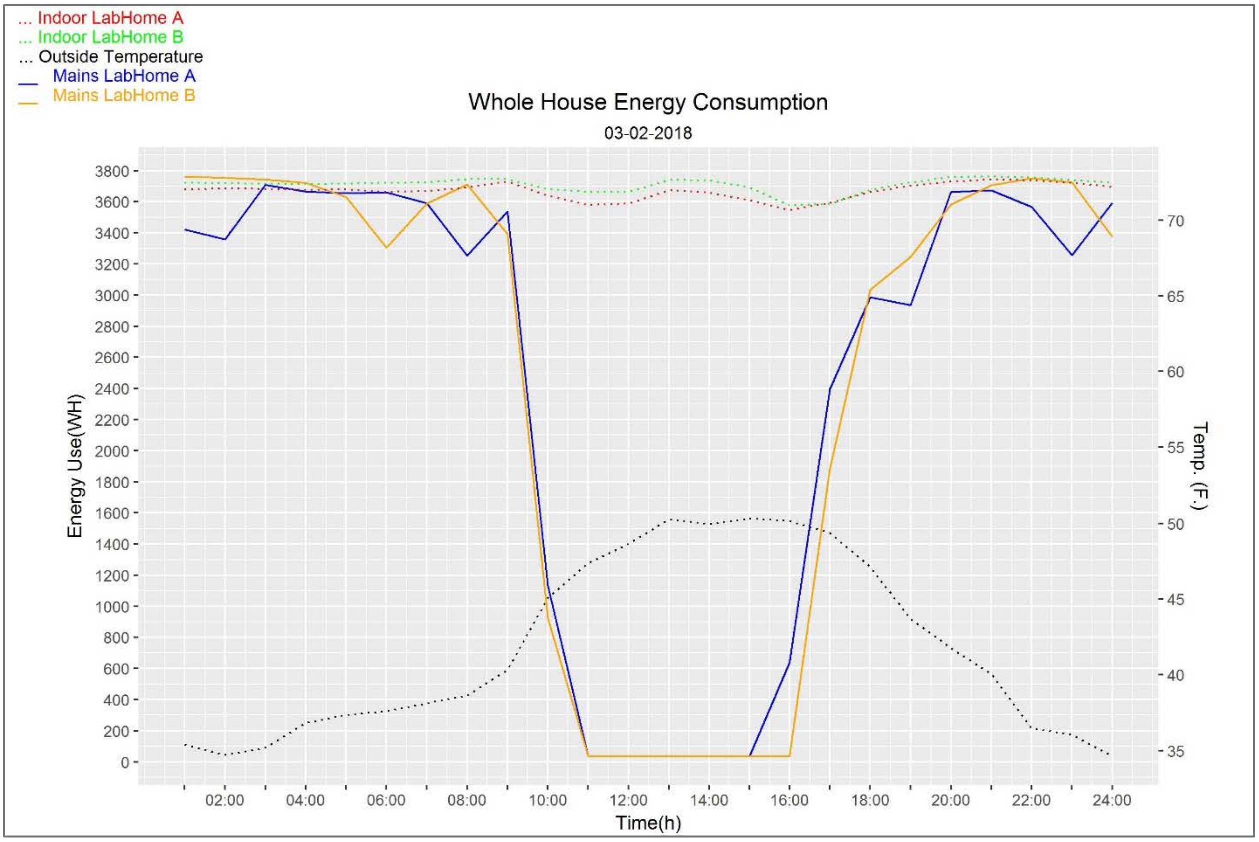

Figure 4.3. HVAC Energy Use of the Baseline (Lab Home A) and Experimental Home (Lab Home B) during Heating Season Baseline

4.2 Building Shell Air Leakage

During the baselining of the homes for each cooling and heating season experiments, the building shell air leakage was measured to ensure similar air-leakage performance between the two homes. The results showed the air leakage of the two homes to be statistically similar, with 95% confidence, as shown in Table 4.12.

During the cooling season, the baseline home had an air-leakage rate of 809.5 ±3.1 cubic feet per minute at 50 Pa depressurization (CFM50) with respect to the outside, and the experimental home had an air leakage of 851.0 ±8.9 CFM50. During the heating season, the baseline home had an air-leakage rate of 911.7 ±1.2 CFM50 with respect to the outside, and the experimental home had an air leakage of 888.8 ±5.1 CFM50.

Heating season blower door data was taken twice after noticing minor air leaks in the baseline home, which were then repaired and then followed by further testing to compare the energy consumption between the two homes. The results for the second blower door testing reflect the decrease in air leakage and are shown in Table 4.2 (Heating Season 2 of 2). The baseline home had an air-leakage rate of 879.8 ±12.9 CFM50 with respect to the outside, and the experimental home had an air leakage of 875.3 ±3.6 CFM50.

A previous triple cell cellular shade study did not demonstrate significant changes in air leakage with the installation of the window attachments (Petersen et al. 2016); therefore, pre- and post-shade installation air-leakage tests were not repeated for this experiment. Considering factors such as experimental error in the measurement and instrument accuracy, the two homes tested equivalent air leakage with 95% confidence. 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) also are presented in Table 4.2 for reference.

Table 4.2. Blower Door Test Results with Window Attachments Installed

	Baseline Home		Experimental Home	
Parameter	Average Value	95% Confidence Interval	Average Value	95% Confidence Interval
Cooling Season (May 2017)				
CFM50[(a)]	809.5	3.1	851.0	8.9
ACH50[(b)]	3.90	0.02	4.09	0.04
ACH_n[(c)]	0.18	0.001	0.19	0.002
Heating Season (1 of 2 – November 6, 2017)				
CFM50[(a)]	911.7	1.2	888.8	5.1
ACH50[(b)]	4.39	0.01	4.28	0.02
ACH_n[(c)]	0.20	0.0003	0.20	0.001
Heating Season (2 of 2—November 27, 2017)				
CFM50[(a)]	879.8	12.9	875.3	3.6
ACH50[(b)]	4.23	0.06	4.21	0.02
ACH_n[(c)]	0.20	0.003	0.20	0.001

(a) Cubic feet per minute at 50 Pascals of depressurization
(b) Lab Homes calculated volume approximately 12,468.95 cubic feet (1500 sq. ft home)
(c) n = 21.5, based on single-story home in climate zone 3, with minimal shielding

4.3 Cooling Season Testing Results

The cooling season testing was performed from May 2017 through September 2017. Cooling was provided by a 2.5-ton, SEER 13 heat pump. To compare and assess the performance of the cellular shades relative to the baseline home, energy use was compared on an average daily basis; however, hourly data was examined to characterize peak period savings and comfort (i.e., indoor temperatures) throughout the experimental period.

4.3.1 Cooling Season – Cellular Shades Thermal Performance

During the thermal performance testing, the cellular shades in the experimental home were either closed throughout the duration of the experiment or set to typical use settings (see Section 3.2.2). In all cases, there was no operation or changes in the position (e.g., moving shades up or down) throughout the day.

Table 4.3 provides a selection of results from the static thermal cooling season experiments. During the cooling season, the shading strategy from an energy-efficiency standpoint is to keep the shades closed as much as possible, as any form of shading would presumably reduce heat gain through the windows and therefore reduce the cooling load. For the Lab Homes testing of the double-cell cellular shades completely covering all windows, the HVAC savings were 25% (3359 watt-hour savings per day) when compared to control home that had no window coverings (see Figure 4.3). The energy savings from insulating cellular shades, drops to 5% when the shades are operated in a typical use manner[1] when compared to the same baseline home with no window coverings. The energy savings results with typical use settings are greatly reduced because the Lab Homes have large south and west-facing living room and dining room windows and experience significant afternoon solar gains when the windows are not fully covered (see Figure 4.4). Nevertheless, the type of shading material does affect savings, regardless of the shade positions, as the cellular shades out-performed vinyl horizontal blinds in the static use setting (i.e., coverings always closed) as well as the typical use setting.

Table 4.3. Cooling Season Thermal Performance Static Testing Results

Experimental home	Baseline home	HVAC savings % (±95% confidence)	Average outdoor temperature (°F)	Average W-hr/day savings
Static use: Double-cell cellular shades always pulled down on all windows	No shades	24.8 (±8.6)	70.0	3,359
Typical use: Double-cell cellular shades; bedrooms closed, living/dining open.	No shades	4.7 (±1.3)	81.1	1,808
Static use: Double-cell cellular shades always pulled down on all windows	Vinyl blinds, static use (always down)	13.3 (±1.3)	76.2	2,650
Typical use: Double-cell cellular shades; bedrooms closed, living/dining open.	Vinyl blinds, typical use operation	5.8 (±0.5)	78.3	1,487

These thermal performance savings estimates for the double-cell cellular shades were fairly similar to the savings results from the triple-cell cellular shades when compared to vinyl shades in a fully deployed position (see Table 2.1 of this report and Peterson et. al. 2016). During the 2015–2016 experiments, the whole-house HVAC savings for the triple-cell cellular shades were 16.6% ±2.9% when compared to vinyl blinds, while the double-cell savings is for the same experiment were 13.3% ±1.3%.

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[1] Where typical use implies that shades are closed in bedrooms but remain fully open in south and north-facing common area rooms and partially open in west-facing living room rooms.

Figure 4.3 shows the peak flattening effect that high-efficiency shading can have on the cooling load of a home (see yellow line of experimental home compared to blue line of baseline control home). This savings, however, will largely be lost if large living room window shades remain open, particularly if those shades are installed on large south and west-facing windows (see Figure 4.4 and Figure 4.5).

Figure 4.5 shows data from July 2, 2017, during which both Lab Homes had window coverings over their windows set to typical use positions throughout the day and evening. The experimental home has double-cell cellular shades while the baseline home has vinyl blinds in typical use positions. On this day, the average outdoor air temperature was 79°F with a high temperature of 91°F. The HVAC energy use in watt-hours for the baseline home (blue) and the experimental home (yellow) are shown along with the indoor air temperatures for both homes (dotted lines). Although the HVAC use profiles are similar for the homes, the peak indoor temperature in the experimental home is slightly lower during the mid-day peak outdoor temperature period, and the average HVAC savings on this day was 6%. Thus, although the peak flattening effect of the shades in negligible with the typical use positions employed in our experiments, there is still a benefit to having more insulating shade coverage for the rooms.

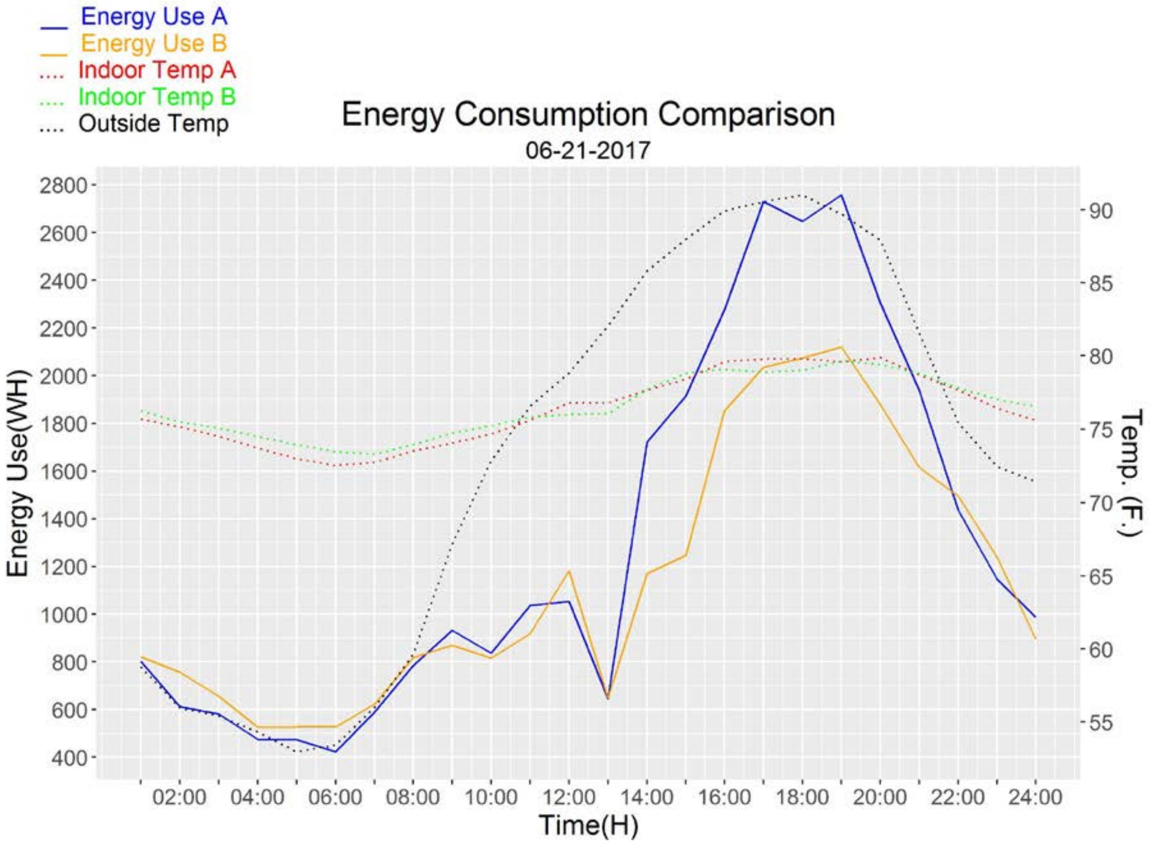


Figure 4.3. Whole-House Cooling Use (solid lines) on a Summer Day with Cellular Shades Closed in the Experimental Home (Lab Home B) and No Shades on the Baseline Home (Lab Home A) Shows Peak Flattening Effect

Figure 4.4. Large West- and South-Facing Windows in Common Area Rooms Allow Considerable Heat Gains in when not Fully Covered by Window Shading

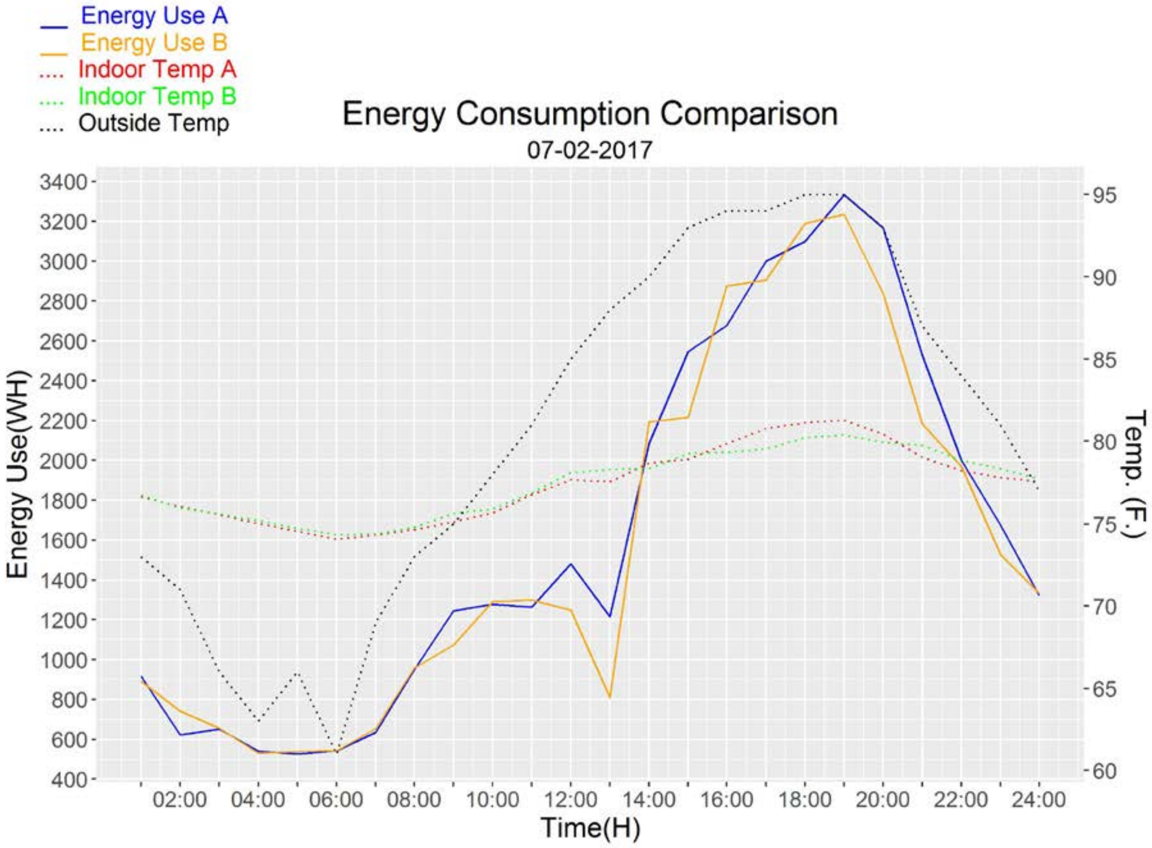


Figure 4.5. Whole-House Cooling Use (solid lines) on a Summer Day with Cellular Shades with Typical Use Settings in the Experimental Home (Lab Home B – yellow line) and Vinyl Blinds with a Typical Use Setting in the Baseline Home (Lab Home A – blue line)

4.3.2 Cooling Season – Optimal Control Strategies

Although the optimal summer shading strategy from an energy-efficiency perspective may be to keep the shades closed all the time, this type of strategy would obviously run counter to a building occupant's desire to see the outdoors and allow in full amounts of natural light. However, keeping the shades closed is typically the setting that building occupants would choose for reasons of security or privacy. Thus, if the home is unoccupied during a summer day, the closed shade setting would be an ideal setting from both energy-efficiency and security standpoints. With this in mind, we examined the effects of two control strategies using the HD Green schedule and an occupancy control scheme that recognizes when the home occupant is away at work during the day.

The HD Green schedule is designed to optimize HVAC operation while allowing some daylighting to accommodate consumer needs for natural daylight (HD Green schedule; see Appendix C). When the cellular shades were operated with the HD Green schedule and compared to the baseline home with typical vinyl slatted shades operated with typical use setting positions, the savings were 15% (Table 4.4). These savings were similar to the savings that were realized with the "Occupancy Sensor" operation scheme (also 15%), which would close the shades during work hours when the home occupants were presumed to be at work. The homes had a constant setpoint of 76°F, and outdoor average temperatures were similar between the two experiments, with high temperatures ranging from 83°F to 95°F during the experimental timeframe.

Table 4.4. Cooling Season Optimal Control Strategies

Experimental home	Baseline home	HVAC savings % (+/- 95% confidence)	Average outdoor temp (°F)	Average W-hr/day savings
Partial optimal control: HD Green schedule for common area rooms, typical use in all other rooms	Vinyl blinds, typical use operation	15.1, (±2.0)	77.4	3,287
Simulated Occupancy Control schedule: Cellular shades closed in the common area from 9AM to 5PM and typical use operation during all other hours	Vinyl blinds, typical use operation	15.2, (±2.2)	76.4	3,814

Figure 4.6 and Figure 4.7 show the whole-house energy use for selected days in both experiments. In both cases, the control strategy was employed only in the common area rooms (i.e., the dining room, kitchen and living room), whereas the bedrooms remain static in typical use positions throughout the experiments. Thus, only five of the nine window shades would need to be operated to realize these savings.

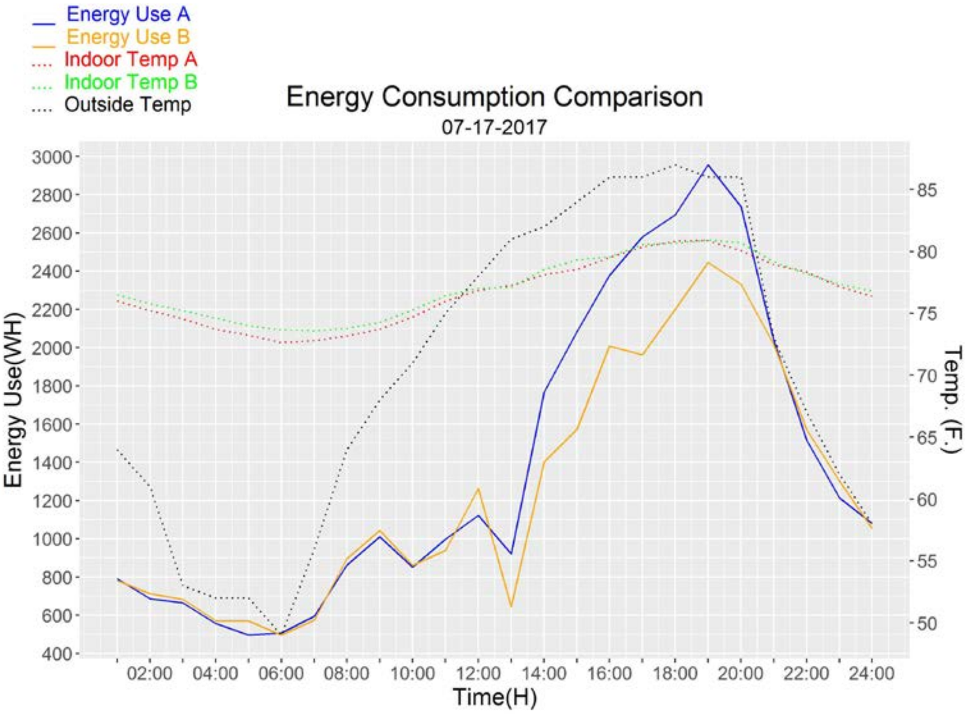


Figure 4.6. Whole-House Energy Use with HD Green Operation in Common Areas in Experimental Home (Lab Home B). Baseline Home (Lab Home A) is equipped with Venetian blinds with typical use settings.

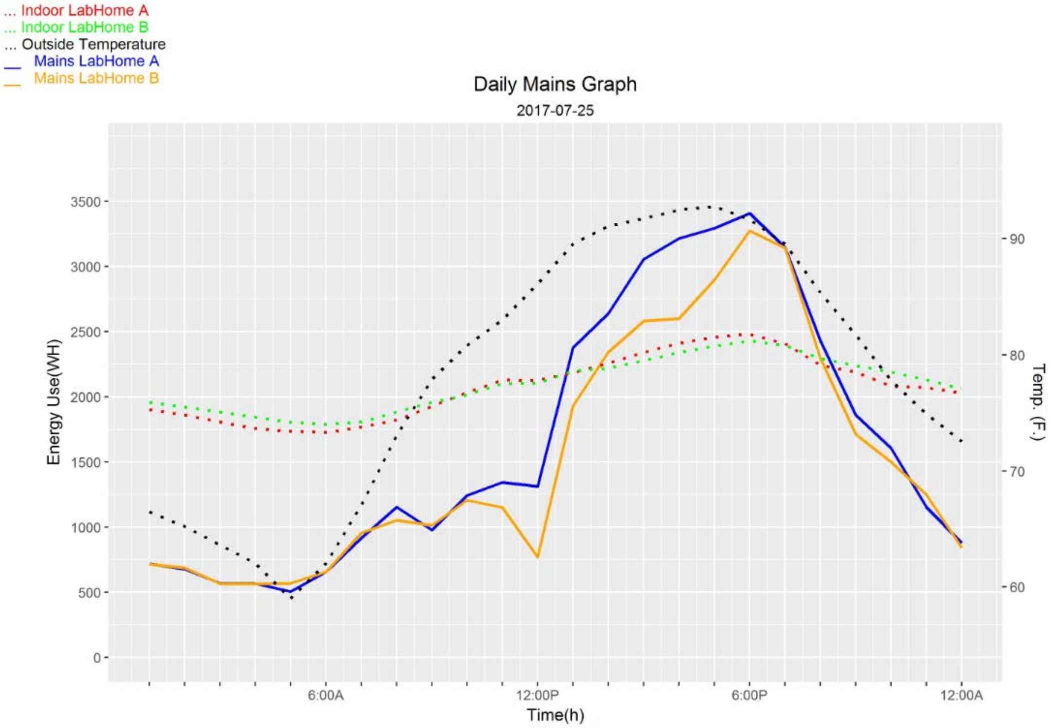


Figure 4.7. Whole-House Energy Consumption “Occupancy Control” in Common Area Rooms in Experimental Home (Lab Home B). Baseline Home (Lab Home A) equipped with Venetian blinds with typical use settings.

These control strategies could be carried out manually or through automation. Occupancy control could be triggered and integrated with any number of smart thermostats that sense when occupants are not home. HD Green Mode is a pre-programmed schedule, but it too could be integrated with a smart device that automatically knows the season and time of day and triggers the appropriate settings based on this information. For both control strategies, the day-to-day savings are consistent, with only a ±2% margin of error.

4.3.3 Cooling Season – Demand Response

A demand-response experiment was designed to examine the effect of pairing the deployment of cellular shades with a 4°F thermostat increase (set-up) during the hottest period of the day, from 3PM to 7PM, in an effort to reduce the peak cooling watt-hours. This was compared to a baseline control home under two separate conditions. In the first experiment, the baseline control home maintained the 76°F throughout the day without a set-up and had typical blinds with typical settings. The savings from this experiment would represent the savings between participants in the demand-response program and a non-participant home (Table 4.5). For this first experiment, the peak temperatures during this 15-day experimental period were high, averaging 98°F and over 8 days with high temperatures in excess of 100°F. Thus, the conditions truly reflected weather conditions that could trigger peak demand events.

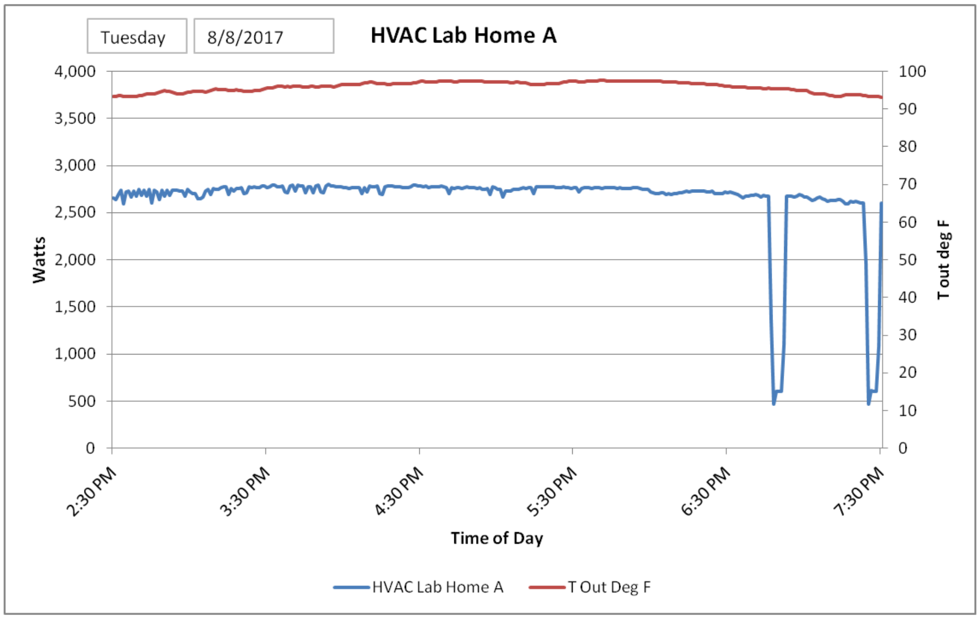
Table 4.5. Cooling Season Demand-Response Experiments

Experimental home	Baseline home	HVAC savings % (+/- 95% confidence)	Average W-hr/day savings	Average Max Peak Demand Reduction (Watts)
Demand response: Cellular shades pulled down during 4-hr peak period and 4°F thermostat increase (set-up) (typical use operation during non-peak hours)	Vinyl blinds, typical use operation, and no thermostat adjustments	15.7 (±2.2%)	4,060	1600
Demand response: Cellular shades pulled down during 4-hr peak period and 4°F thermostat increase (set-up) (typical use operation during non-peak hours)	Vinyl blinds, typical use operation, and 4°F thermostat set-up during 4-hr peak period	16.6 (±2.94)	2,998	700

Figure 4.8 shows the HVAC cycling during the peak period on August 8, 2017, when the peak outdoor temperatures reached 100°F. During the peak period, the HVAC in the baseline home where typical blinds are installed and used in a typical manner and no thermostat set-up occurs, is cycled on almost constantly throughout the 4-hour peak period as the system struggles to keep the indoor temperatures to the 76°F setpoint. Meanwhile, in the experimental home where the cellular shades are closed and the thermostat set-up occurs, the HVAC cycles on and off and maintains the same indoor setpoint as the baseline home.

The average daily savings during this experiment was 4060 watt-hours, and the percentage HVAC savings was 16% and maximum peak demand reduction of 1600 Watts during the 4-hour peak period when averaged over the 12 experimental days examined. This savings and demand reduction reflect savings from both the thermostat set-up and the shades. The maximum peak demand reductions were typically achieved between 3PM and 4:30PM during the experimental period. To determine how much the shades both contribute to the responsiveness and overall demand period savings, a second experiment was run in which the thermostat is set-up by 4°F during the same time period in both homes, but the baseline home had typical vinyl horizontal blinds operated in a typical use fashion throughout the day.

The daily average HVAC savings during this experiment was 17% and the average peak demand reduction was 700 watts over the experimental period. The only thing differences between the two homes during the second demand response experiment were the type of shade and the full deployment of the shades in the late afternoon in the experimental home. Outdoor temperatures were not as hot during the second experiment; thus, the overall cooling load of the homes was lower than the first experiment.



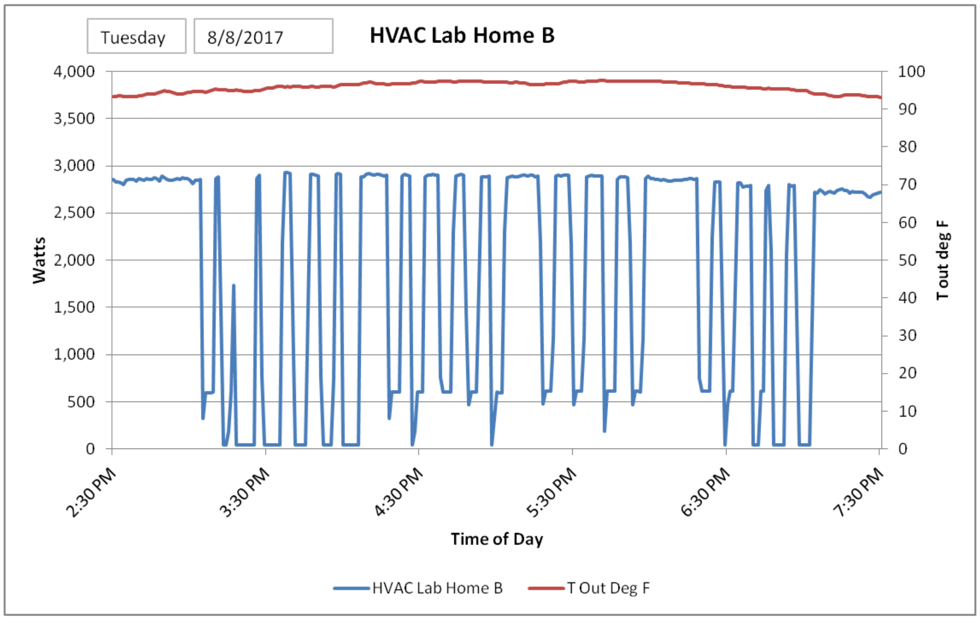


Figure 4.8. HVAC Cycling with Demand Response and Cellular Shades Employed in the Experimental Home (Lab Home B) but not in Baseline Home (Lab Home A). Outdoor temperature highs of 98°F occurred during this period.

Figure 4.9 shows that not only did the deployment of the cellular shades make the thermostat set-up more effective in reducing watt-hours when it occurred, but it also reduced the demand between the 3PM to 7PM period. Based on the watt-hour savings comparison between these two experiments, the deployment of the cellular shades during the peak period event is estimated to contribute over two-thirds of the overall watt-hour HVAC reduction during the peak period demand response. These findings would suggest that pairing shade use with a demand-response program that targets thermostat increases during the peak period (3PM to 7PM in this case) could improve the effectiveness and overall savings from the demand-response programs.

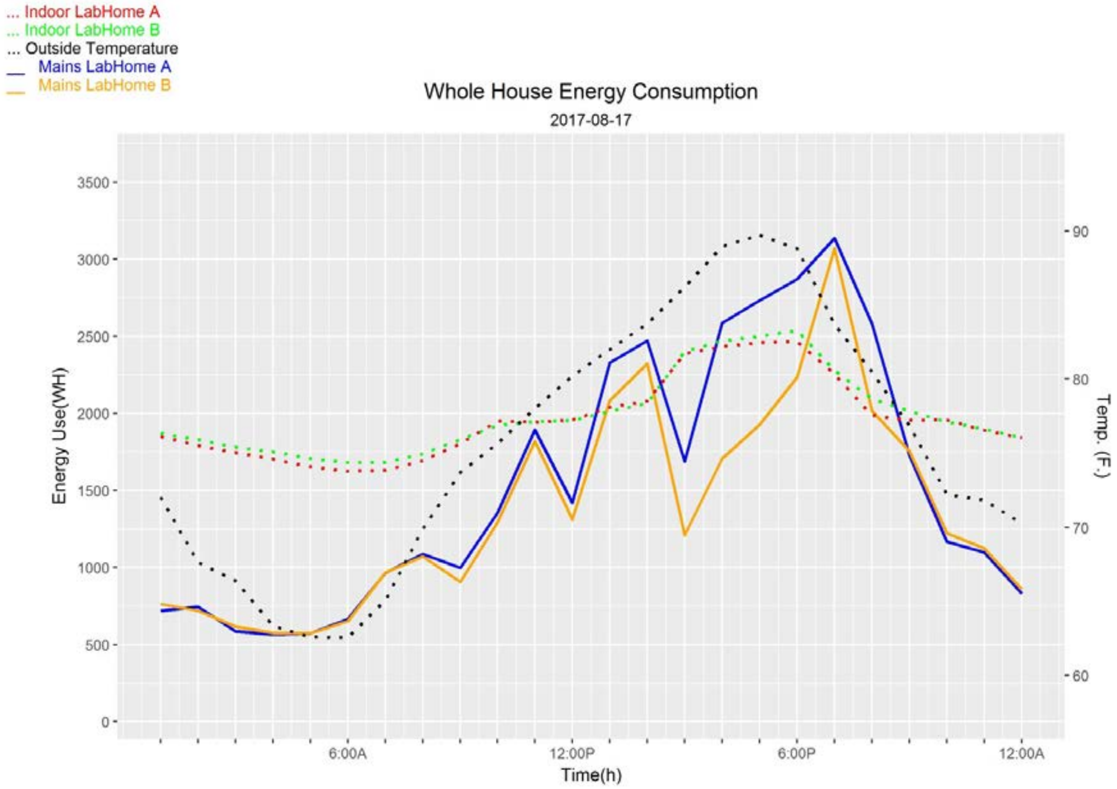


Figure 4.9. Whole-House Cooling Use with Thermostat Set-Up during Peak Period (3PM-7PM). Yellow line depicts experimental home (Lab Home B) energy use with the shades down in common area in addition to thermostat set-up.

4.4 Heating Season Testing

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 the 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 energy performance of the window attachments was initially evaluated from October 2017 through March 2018.

As with the cooling season experiments, double-cell cellular shades were installed in the experimental homes, while Venetian horizontal slatted blinds were installed in the baseline control home.

4.4.1 Heating Season – Cellular Shades Thermal Performance

From an energy-efficiency perspective, the optimal operating schedule for insulated cellular shades during the winter heating season is more nuanced than the “keep them closed as much as you can” summer cooling season strategy. One of the key findings was that beneficial heat gains through the south- and west-facing windows significantly contribute to reducing the heating load during the daylight hours, particularly on a cold sunny day with the clear-glass (i.e., not low-e) windows, and much of these beneficial heat gains are not realized when the shades are pulled down during the daylight hours.

Table 4.6 provides the results of the static and typical use testing of cellular shades during the heating season. The overall thermal insulating performance of the cellular shades compared to the vinyl blinds is best revealed with the experiment that compares both shades fully closed. Although this would not necessarily be considered the optimal operation strategy, by eliminating the effect of solar gains through the windows, this comparison reveals the effect of the higher R-value of the insulating shades, which produces a 9.3% HVAC savings when compared to vinyl blinds. The performance of the double-cell cellular shades is comparable to the triple-cell cellular shades, which realized a 10.5% HVAC savings when compared to vinyl shades during the heating season (see Table 2.1 of this report).

Table 4.6. Heating Season Static Thermal Performance of Cellular Shades

Experimental home	Baseline home	HVAC savings % (±95% confidence)	Duration	Average W-hr/day savings
Static use on cloudy days only: Double-cell cellular shades always pulled down on all windows	No shades	5.0* (±1.3)	6 days	4,416
Static use: Double-cell cellular shades always pulled down on all windows	No shades	2.4 (±3.2)	9 days	1,970
Static use: Double-cell cellular shades always pulled down on all windows	Vinyl blinds, static use (always down)	9.3 (±1.9)	6 days	7,011
Typical use: Double-cell cellular shades; bedrooms closed, living/dining open.	Vinyl blinds, typical use operation	2.0 (±1.3)	4 days	1,505
* Minimum savings on cloudy days due to issues with drifting thermostat setpoints (i.e., experimental home was heating to a higher setpoint)				

Figure 4.10 shows the HVAC heating consumption for each of the homes on a sunny day with the cellular shades fully closed in the experimental home, no shade covering in the baseline home, and thermostat setpoints 71°F in both homes. As seen in Figure 4.10, HVAC consumption drops to zero in the middle of the day in both homes, but it drops earlier in the baseline home, which has no shades. The indoor temperature of the baseline home also increases several degrees above that of experimental home despite the fact that no HVAC is employed during this time. Even with the insulating benefit realized in the evening and early morning hours in the experimental home, the net savings on this day were negative (−5%). On cloudy days, however, these beneficial heat gains were less pronounced, and modest HVAC savings (5%) from the added insulation were realized on these cloudy days during the December 2017 experimental period (Figure 4.11).

On average, over 13 experimental days, with a mix of weather and cloud cover and average outdoor temperatures of 32°F, modest savings of 2% were realized from the installation and full deployment of cellular shades (and compared to a home without shades) or when set to typical use positions (and compared to a home with typical Venetian blinds operated in typical use fashion).

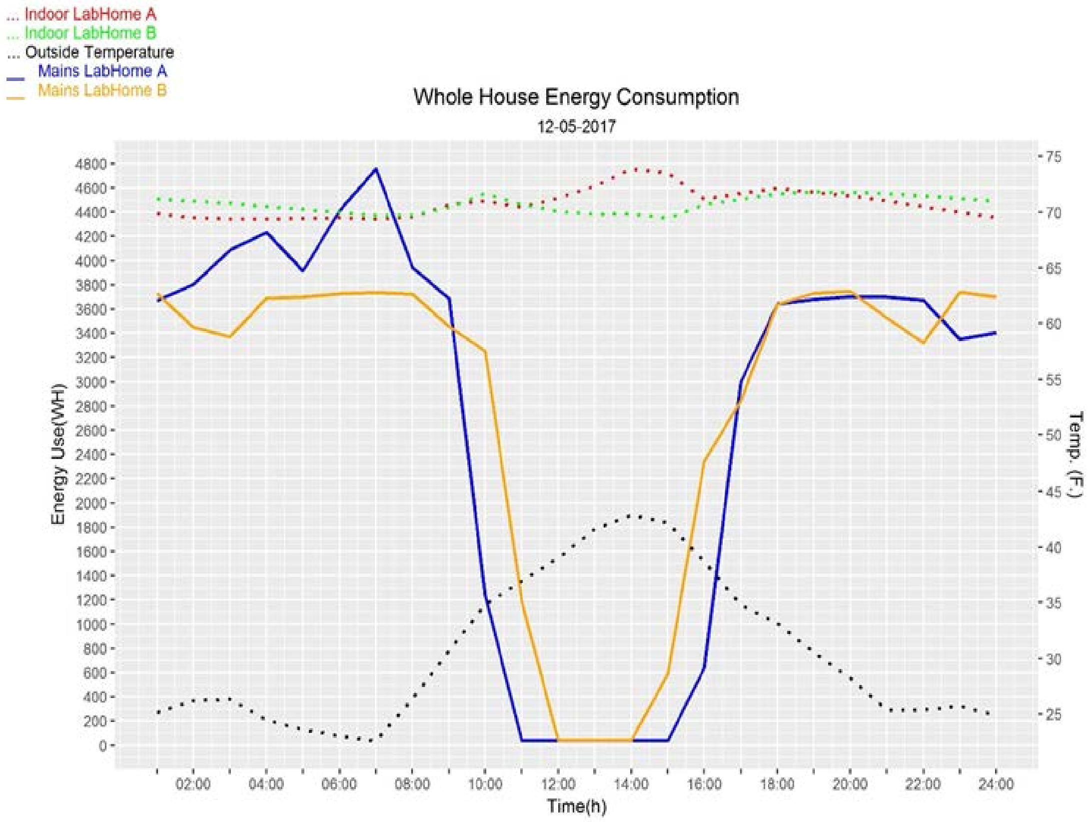


Figure 4.10. Whole-House Energy Use on a Winter Day with Cellular Shades Covering All Windows in the Experimental Home and No Shades Covering Windows in Baseline Home

Figure 4.11. Savings Realized with Shades Pulled Down on a Cloudy Day (left photo taken on December 11, 2017, HVAC savings of 5% realized on this day). Negligible or negative average watt-hr/day savings realized on sunny days with few clouds (e.g., negative savings on December day with few clouds, right photo).

4.4.2 Heating Season – Optimal Control Strategies

Consistent HVAC savings were realized in the experimental home with cellular shades when optimal control strategies were employed. Table 4.7 provides the testing results for the experiments that involved operating cellular shades in an optimized manner in order to capture the beneficial heat gains throughout the day and insulate the window from thermal losses during the evening and early morning hours. The Partial Optimal Control experiment utilized the HD Green schedule, which opens and closes blinds based on orientation and time of day in order to allow beneficial heat gains while minimizing heat losses. The Best Practices experiment opened the shades at 6AM and closed them at 6PM. For the Partial Optimal Control experiment and Part I of the Best Practices experiment, the control strategy is only employed in the common areas rooms of the dining room, kitchen and living room, where the bedrooms remain static in typical use positions throughout the experiments. Thus, only five of the nine window shades would need to be operated to realize these savings.

Table 4.7. Heating Season Optimal Control Strategies

Experimental home	Control Home	HVAC Savings % (±95% confidence)	Duration	Average W-hr/day savings
Partial Optimal Control: HD Green schedule for common area rooms, typical use in all other rooms	Vinyl blinds, typical use operation	6.7 (±1.0)	5 days	4,728
Best Practices I: Operating shades in common area only. Shades open at 6AM and closed at 6PM.	Vinyl blinds, typical use operation	5.4 (±1.2)	9 days	3,007
Best Practices II: Operating shades in all of the home. Shades open at 6AM and closed at 6PM.	Vinyl blinds, typical use operation	8.7 (±1.2)	3 days	5,445

For the heating season testing, a variety of different operational settings that opened the shades at least to some degree during the day and closed them at night were able to produce consistent HVAC savings (average of 5–9%) in the home with cellular shades, whether it was just partial operation of the large west- and south-facing common areas windows, or full operation of all windows. When all the windows with cellular shades were opened during the day and closed at night in the experimental home (Figure 4.12), the average HVAC savings were 9% compared to the home with typical vinyl blinds operated in typical use fashion.

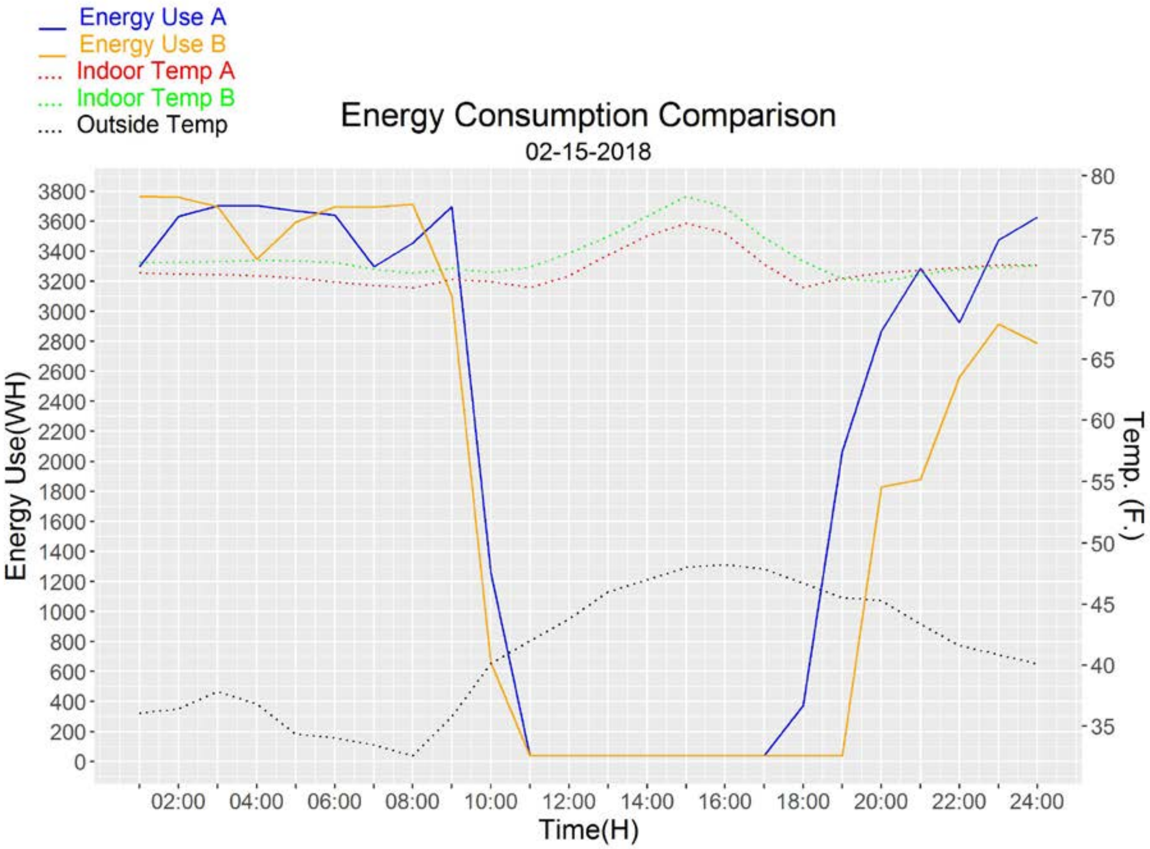


Figure 4.12. Whole-House Energy Consumption in Lab Homes on a Winter Day with Cellular Shades Open during the Day and Closed at Night in Lab Home B, Experimental Home, (i.e., Best Practices) and Typical Use (vinyl blinds) in the Baseline Home (Lab Home A).

4.4.3 Heating Season – Thermostat Setback and Comfort Benefits

During the winter season, utilities will often experience peak demand periods in the evening and morning hours as residents wake up or return home from work and start turning on lights and appliances and possibly heating up their homes. This peak demand period can be flattened somewhat if thermostats are programmed with a setback temperature. To examine the effect of cellular shade deployment on thermostat setback strategies, we added a few days to the Best Practices experiments that included thermostat setbacks in both Lab Homes. For this experiment, cellular shades were closed during the evening hours, and temperature was setback 5°F (from 9 PM to 6 AM) in both the experimental and baseline homes. In the baseline home, Venetian blinds were used with typical use settings. Figure 4.13 shows that the experimental home with cellular shades maintained warmer temperature longer after the thermostat setback. Average HVAC savings this day (February 7, 2018) were 5% over a 24-hour period.

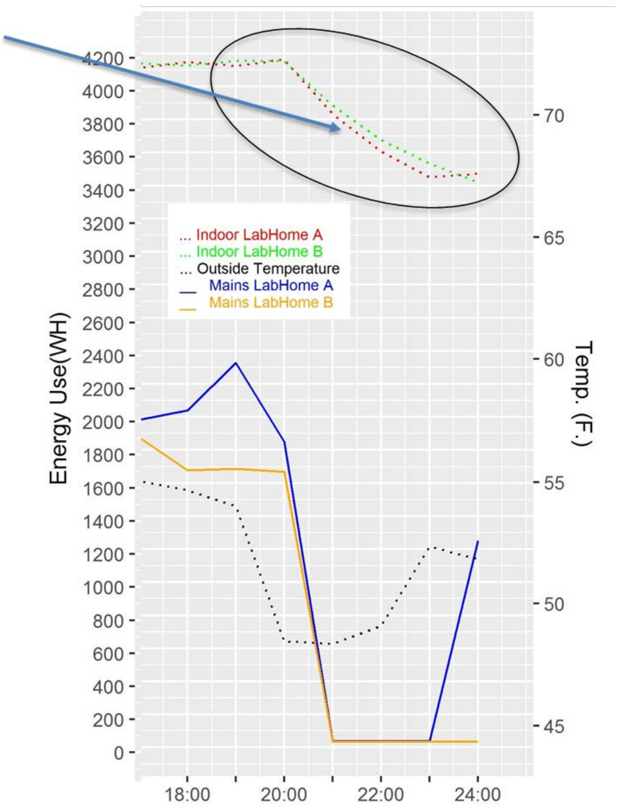


Figure 4.13. Whole-House Energy Savings with Thermostat Setback in the Evening

4.4.4 Heating Season – "Smart" Dynamic Control

The final heating experiment employed a dynamic control algorithm developed for the experiment, which decides on a preference for the window shade setting. This is a function of the space temperature, the thermostat setpoint temperature, and the thermostat mode (heating). The algorithm was designed to control cellular shades, by estimating the total heat flux (W/m^2) into or out of the window, both when it is uncovered, and when it is covered by the cellular shades at the current time. The estimated heat flux is based on the thermal properties of the window and shades and coupled with interior and exterior temperatures, optical properties of the window and shades, and the estimated incident solar radiation on the exterior of the window (see Appendix D of this report). This control strategy was implemented for demonstration purposes and is based purely on optimizing the energy performance of the window system. Other practical considerations such as views, privacy preferences, and daylighting are not taken into accounted. During this period, the HVAC thermostat was set at 71°F in heating mode.

The smart dynamic control experiment was run for 24 days where the average whole-house HVAC saving was 5.5% ±3.5%. This experiment was mostly run during the winter shoulder season when the weather and cloud cover were quite variable with an average outdoor temperature of 48.5°F. Although savings were achieved with the algorithm on most days, the overall saving was much more variable for this control strategy relative to either the HD Green Mode or the Best Practices control strategy, where results remained within ±1.2% with a 95% confidence interval. Thus, it appears that simple winter shading strategies that open window coverings during daylight hours and closes them at sundown will provide optimal savings. Nevertheless, "smart" controls that can track the outdoor temperatures and seasons could help maintain comfort and produce savings throughout the year and could be beneficial to making automatic adjustments as seasons change.

5.0 Key Findings and Savings Potential

There are several key findings from the experiments that can inform the original experimental questions as presented in Section 3.3. These questions and some follow-on implications are presented below.

1. *What is the whole-home energy savings potential from the installation of double-cell cellular shades installed over double-pane, clear-glass windows when compared to a home with no window coverings?*

   During the summer cooling season the application of double-cell cellular shades saved from 5% to 25% of whole-house HVAC energy use when compared to a home without window coverings. The 25% savings is generated when the shades are closed all day. During the winter, the savings from fully closed cellular shades varied depending on the weather and cloud cover, with average savings of 5% during very cloudy days and an average savings 2% over the experimental period. The savings from fully closed cellular shades were negligible on sunny days when the mid-day solar heat gains were not fully realized in the home with covered windows. Although no experiments were run that compared optimally operated double-cell cellular shades to a home with uncovered windows, previous experiments with triple-cell cellular shades (Petersen et al., 2016) realized 14% HVAC savings when compared to a home with no window coverings and when operated with the HD Green schedule. Based on the comparison of thermal performance revealed in other similar experiments run on double-cell and triple-cell shades, we estimate that savings for the double-cell shades would be approximately 12% when operated with the HD Green schedule and compared to a home with no shades.

2. *What is the whole-home energy savings potential from the installation of double-cell cellular shades installed over double-pane, clear-glass windows when compared to a home with vinyl horizontal blinds (the most ubiquitous window covering on the market)?*

   During the summer cooling season the application of double-cell cellular shades saved from 6% to 13% whole-house HVAC energy use when compared to a home with vinyl horizontal slatted blinds (with slats angled to a fully closed position). The 6% savings is realized when shades in both homes are operated with typical use settings, and the 13% savings reflects savings from cellular shades when both window coverings are fully closed. An average savings of 15% can be generated consistently (in comparison to typical vinyl shades in typical settings) when cellular shades are closed for at least some portion of the afternoon during the summer. During the winter, the average HVAC savings from the use of cellular shades in comparison to a home with vinyl blinds ranges from 2-9% when shades are either set to typical use settings (2% savings) or fully drawn down and not operated (9% savings). Optimally operating the shades in the winter throughout the home can consistently generate 9% savings when compared to vinyl blinds operated in typical use settings.

3. *What is the impact of operation and optimal control schemes on the energy savings of the double-cell cellular shade when compared to a home that operates standard window coverings (i.e., vinyl horizontal blinds) in a typical use fashion (as defined in Section 3.2.2 of this report)?*

   During both the summer and winter months, much of the savings potential of insulated cellular shades will be lost when operated in the typical use fashion as defined in Section 3.2.2 of this report. Although these experimental results would suggest that the HVAC energy savings potential of upgrading households with low-efficiency window coverings and installing insulated cellular shades in homes without window coverings would be significant,[1] even when shades are operated in a

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[1] E.g., estimated to exceed 100 trillion Btus across the U.S. The calculation is based on total residential heating and cooling consumption of 4225 TBtu and 631 TBtu, respectively (DOE 2018), and assumes 2% and 6% average heating and cooling savings, respectively, for homes upgrading from vinyl blinds to cellular shades and heating and

typical use fashion, this savings potential more than quadruples[1] when “smart,” energy-efficient operation of the shades occurs throughout the year. This would suggest that, whether through automation or through manual operation, there is a need in this sector for efficiency and utility programs to help consumers make informed product choices and to help educate and incentivize “smart” energy-efficient operation of window coverings to help consumers fully realize energy savings from high-efficiency window attachments.

4. *What are some enhanced automation and dynamic features that can aid in energy savings? What is the difference in energy savings of cellular shades that are dynamically controlled through a thermostat, external weather data, or other local indoor temperature compared to vinyl horizontal blinds that are operated in a typical fashion? Can the control scheme be optimized based on external parameters and the cardinal direction of windows during key points of the day?*

   Although savings were achieved with the dynamically controlled algorithms that relied a combination of sensors and weather information, these same savings also could be achieved very consistently with predefined schedules, such as the HD Green schedule, that are optimized based on season, orientation of the windows, and location of the home. Even simpler schedules that open shades during the day in the winter and close them at night were able to achieve consistent and significant savings. In the summer, shading programs that close shades as much as possible, such as a predefined schedules or an occupancy controller that closes shades when the home or room is unoccupied, are effective at achieving maximum savings.

5. *Can dynamically controlled shades be used as grid-responsive devices? If integrated with HVAC conservation, could the shades help improve energy savings and/or comfort to the building occupant?*

   The PowerView Motorization automation used in this experiment was fairly easily controlled by the multi-sided, grid-friendly VOLTTRON platform, suggesting that this form of control could be responsive to external signals, similar to any other thermostatically controlled device in the home. Furthermore, the demand-response experiments demonstrated that pairing cellular shade operation with thermostat adjustments helps reduce HVAC usage during peak demand periods and potentially helps improve comfort of the occupant during thermostat setbacks and peak period events.

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cooling savings of 2% and 5%, respectively for homes currently without window coverings that install cellular shades.

[1] E.g., estimated to be 430 TBtus across the U.S. The calculation assumes 9% and 15% average heating and cooling savings, respectively, for homes upgrading from blinds to cellular shades and heating and cooling savings of 15% and 12%, respectively for homes currently without window coverings that install cellular shades. (Latter percentage savings are based on Petersen et al. 2016 findings.)

6.0 Conclusions

During the 2017–2018 heating and cooling season, experiments were conducted in PNNL's side-by-side Lab Homes to test the thermal performance and effects of dynamic control of HD Duette Architella Elan double-cell cellular shades. The whole-home HVAC use for the experimental home in which cellular shading technology was installed was compared to the whole-home HVAC use in a baseline home that had horizontal slatted vinyl blinds. The blinds in the baseline home were operated in a manner that is "typical" for residential homes based on a DOE behavioral study related to window attachment operation (D&R 2013). The experiments were specifically designed to examine persistence of savings with dynamic and potentially automated operation. Experiments also were designed to examine the potential for dynamic shading use as a demand-response peak load reduction in the residential sector. The results of all the experiments are summarized in Table 6.1.

Table 6.1. Average HVAC Savings of the Double-Cell Cellular Shades (Lab Homes testing during 2017–2018**)**

Experimental Home	Baseline Home	Season	HVAC savings (Average daily %)
Static use: Double-cell cellular shades always pulled down on all windows	No shades covering windows	Cooling	24.8 (±8.6)
		Heating	2.4 (±3.2)
Typical use: Double-cell cellular shades; bedrooms closed, living/dining open.	No shades covering windows	Cooling	4.7 (±1.3)
		Heating	Inconclusive
Static use: Double-cell cellular shades always pulled down on all windows	Vinyl blinds, always pulled down	Cooling	13.3 (±1.3)
		Heating	9.3 (±1.9)
Typical use: Double-cell cellular shades; bedrooms closed, living/dining open.	Vinyl blinds, typical use operation	Cooling	5.8 (±0.5)
		Heating	2.0 (±1.3)
Partial Optimal Control: HD Green schedule for common area rooms, typical use in all other rooms	Vinyl blinds, typical use settings	Cooling	15.1 (±2.0)
		Heating	6.7 (±1.0)
Occupancy Control schedule: Cellular shades pulled down in common area from 9AM to 5PM and typical use operation during all other hours	Vinyl blinds, typical use settings	Cooling	15.2 (±2.2)
Best Practices I: Operating shades in common area only. Shades open at 6AM and closed at 6PM.	Vinyl blinds, typical use settings	Heating	5.4 (±1.2)
Best Practices II: Operating shades in all rooms of the home. Shades open at 6AM and closed at 6PM.	Vinyl blinds, typical use settings	Heating	8.7 (±1.2)

High-efficiency cellular shades have significant energy-saving potential during the summer cooling season (25% HVAC savings), but this savings drops considerably if the larger view windows of a home remain uncovered during the day, particularly if these are west- or south-facing windows. High-efficiency cellular shades have significant energy-saving potential during the winter heating season, but some of the larger south- and/or west-facing window shade have to be operated (i.e., up during the day and down at night) to fully realize these savings benefits.

During the summer months, cellular shades operated in typical use fashion produce HVAC savings; however, when high-heat-gain windows (i.e., large windows on west and south side of a home) are left uncovered, HVAC savings were only around 5%. In all cases and operational scenarios, however, cellular shades out-performed typical vinyl Venetian blinds (6–15% HVAC savings with cellular shades) during the summer months. During the winter, cellular shades operated in typical use fashion produce modest HVAC savings; however, the insulating benefits of cellular shades are largely lost when operated with typical use settings in which there is no operation throughout the day. Nevertheless, cellular shades out-performed typical vinyl Venetian blinds under the typical use scenario (2% HVAC difference) as well as for static (i.e., fully closed) scenarios (9% HVAC difference) during the winter months.

Relative to typical Venetian blinds used in typical static manner, double-cell cellular shades operated under multiple control strategies (whether executed manually or through automation) provided consistent energy savings benefits during both the summer and winter months. With automated integrated controls, cellular shades could be coupled with thermostat setbacks to enhance residential demand- response programs and improve occupant comfort. With automated integrated controls, cellular shades could be coupled with thermostat setbacks to enhance residential comfort and energy savings. Smart control algorithms can be employed to achieve year-round savings; however, seasonal schedules, whether implemented through automation or manually, can also achieve consistent savings.

While approximately 80% of the 118 million U.S. residential housing units have some form of window covering, more than 80% of these installed window attachments are made up of relatively low-efficiency coverings (e.g., vinyl blinds) (Bickel et al. 2013; DOE 2018). There would therefore appear to be a large market opportunity to shift consumers from less efficient window attachment products toward higher efficiency products such as high-efficiency cellular shades. In fact, based on the results of the experiments described in this report, the HVAC energy savings potential of installing insulated cellular shades in homes without window coverings and upgrading households with low-efficiency window coverings would exceed 100 trillion Btus, even when shades are operated in typical use fashion. This savings potential more than quadruples to 430 TBtus when “smart” energy-efficient operation of the shades occurs throughout the year. This finding would suggest that whether through automation or manual operation, there is a need in this sector for efficiency and utility programs to help consumers make informed product choices and to help educate and incentivize “smart” energy-efficient operation of window coverings to help consumers fully realize energy savings from high-efficiency window attachments.

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Appendix A – Monitoring Points

Table A.1. Electrical Points Monitored

Performance Metric	Monitoring Method/Points	Monitored Variables	Data Application
Whole-Building Energy Use	Electrical panel mains	kW, amps, volts	Comparison between homes of • power profiles • time-series energy use • differences and savings
HVAC Energy Use (heat pump)	Panel metering compressor	kW, amps, volts	Comparison and difference calculations between systems of • power profiles • time-series energy use • differences and savings
	Panel metering air handling unit	kW, amps, volts	
	End-use metering condensing unit fan/controls	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 • 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 A.2. Temperature and Environmental Points Monitored

Performance Metric	Monitoring Method/Points	Monitored Variables	Data Application
Space Temperatures	13 Ceiling-hung thermocouples/1–2 sensors per room/area, and 1 HVAC duct supply temperature per home	Temperature (°F)	Comparison and difference calculations between homes of • temperature profiles • time-series temperature changes
	2 mean radiant sensors per home (main living area, master bedroom)	Temperature (°F)	
Glass Surface Temperatures	22 thermocouples (2 sensors per window interior/exterior center of glass); west window with six sensors. 2 thermocouples per home to measure temperature between the primary and storm windows.	Temperature (°F)	Comparison and difference calculations between homes of • 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 • profiles by window and 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 and one to temperature and other data collection. 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 from the outside of the each home to the inside, 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 A.1 displays the temperature measurement points that were placed on one window facing each cardinal direction, except east.

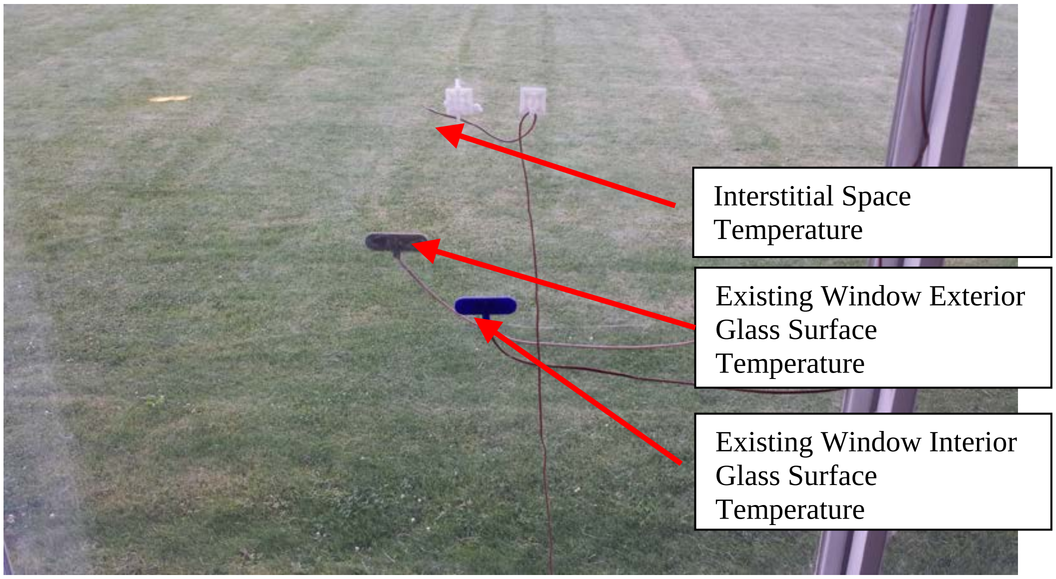

Figure A.1. Window Temperature Measurement Points

Appendix B – Lab Home Commissioning Results

Figure B.1 shows the lighting energy consumption in both homes on August 26, 2017, during the second baseline check experiment. This is one of the sub-metered graphs that we look at to see how the simulated use between the two homes are remained identical. As we can see below, there is a slight variation between the two homes when the curve peaks. The goal for these sub-metered graphs would be that they are exactly the same, so that the constant factors between the two homes are exactly the same also. This small variable does contribute to the differences that we do notice between the two homes, but the impact on the experiments that we are conducting is minimal.

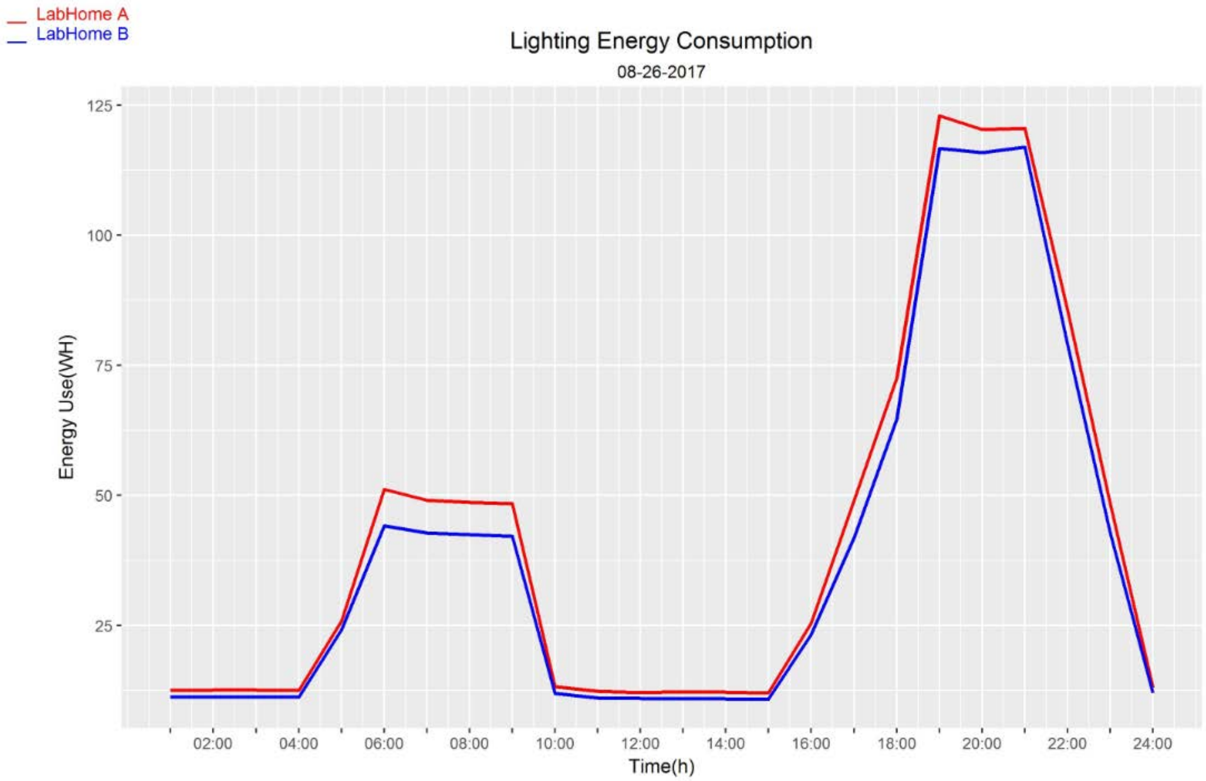

Figure B.1. Lighting Energy Consumption Graph Second Baseline Check Experiment

Another example of a sub-metered graph is the Figure B.2 (Occupancy Energy Consumption graph) produced for August 28, 2017 during the second baseline check experiment. This graph is a constant reading between the two homes and it should be identical, and that is what we are seeing here. This graph showing that the lines are, for the most part, directly overlapping means that the data we are collecting about the simulated occupancy in the house is the same in regard to the objects that fall under this category of simulation.

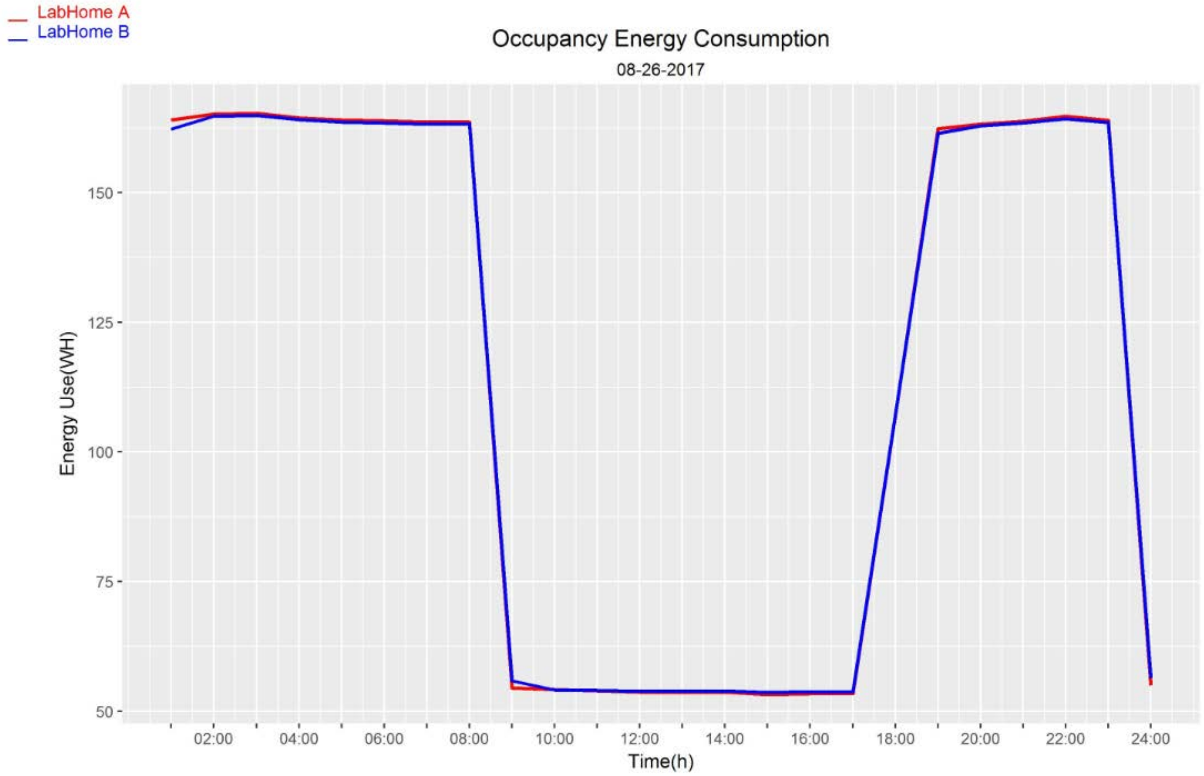

Figure B.2. Occupancy Energy Consumption Graph Second Baseline Check Experiment

This sub-metered graph is the Equipment Energy Consumption graph produced for 8/28/2017 during the second baseline check experiment. The equipment being simulated for occupancy is overlapping the entire time. This is the goal of the simulated occupancy so that it can remain a constant factor between the two homes.

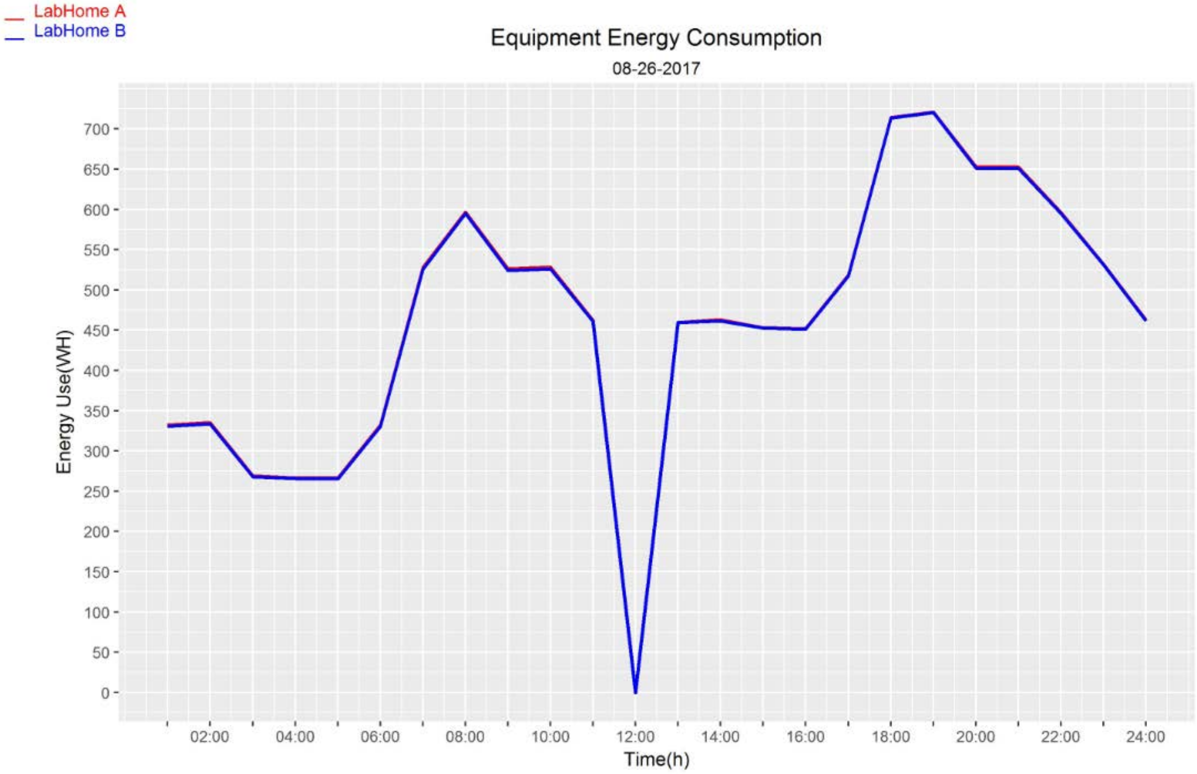

Figure B.3. Equipment Energy Consumption Graph Second Baseline Check Experiment

Appendix C – HD Green Mode Operation Schedule

Developed by Hunter Douglas (HD), 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 C.1. Optimum Efficiency Window Covering Timetable for Richland, Washington (46° Latitude)

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

Appendix D – “Smart” Control Algorithm for Automated Cellular Shades

A control algorithm has been developed by PNNL to control Hunter Douglass cellular shades in the Lab Homes via VOLTTRON. The algorithm works by estimating the total heat flux (W/m^2) into or out of the window, both when it is uncovered (see Equation 1), and when it is covered (see Equation 2) by the cellular shades at the current time. The estimated heat flux is based on

- The thermal properties of the window and shades, coupled with the interior and exterior temperatures
- The optical properties of the window and shades, coupled with the estimated incident solar radiation on the exterior of the window (see Section D.1 for more details). The incident solar radiation is estimated based on solar angle calculations and the assumed impact of local cloud cover on attenuating clear sky solar radiation.

Next, the algorithm decides on a preference for the window to provide either heating or cooling to the space (see Section D.2). This preference is a function of the space temperature, the thermostat setpoint temperature, the thermostat heating or cooling mode, plus some strategic (preheating or pre-cooling) preference based on the time of day and the forecast high or low temperature.

With the preference for heating or cooling established, the control action (shades up or down) is decided based on the estimated heat fluxes of the two control options. A preference for cooling would lead to the control option that provided the lowest heat flux into the house (or highest heat flux out of the house), and vice versa.

This control strategy is for demonstration purposes and is based purely on optimizing the energy performance of the window system. Other practical considerations like views, privacy preferences, and daylighting are not accounted for.

Figure D.1 shows an input/output diagram of the control algorithm, including both static inputs (which must be defined for each window by the installer), and the dynamic inputs, which include live data from the thermostat, plus live and forecast data from the weather service (in this case Weather Underground). Static inputs include things like the window orientation, geographic parameters like latitude (λ), longitude (Lloc) and time zone, plus the thermal and optical properties of the windows and shades, which can be estimated via default values if unknown. The output of the algorithm is the command for the shades, either up or down, at each control time step. These include the window U-factor (U_{window}), the window solar heat gain coefficient ($SHGC_{window}$), the solar transmissivity of the shades ($T_{solar,shades}$) and the effective R-value of the shades, R_{shades}.

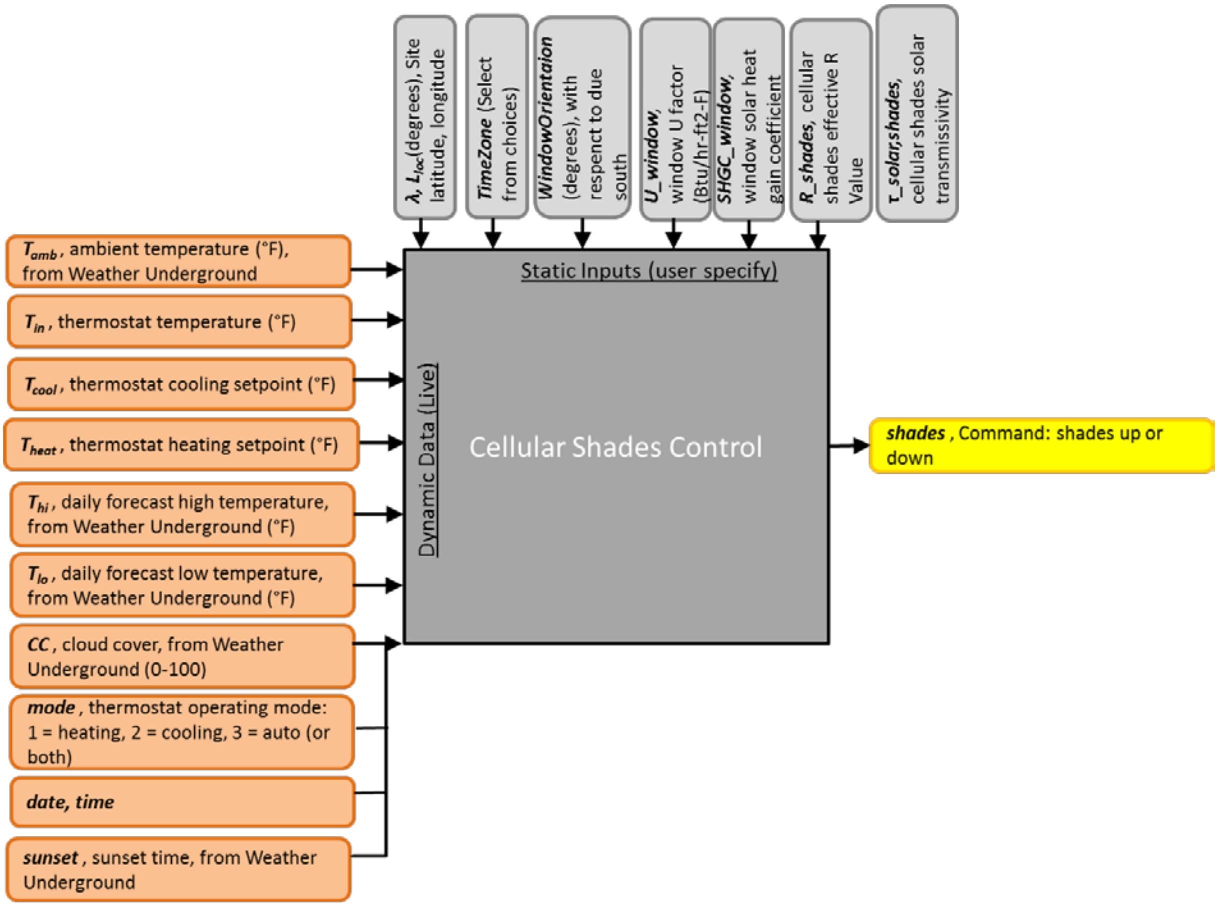

Figure D.1. Input-Output Diagram for Cellular Shades Control Algorithm

D.1 Estimating Heat Flux Across the Window

The heat flux across the window is the sum of the thermal heat gain and the solar heat gain. When the shades are drawn, the thermal heat gain includes the impact of both the thermal resistance from the window, plus the cellular shades. When the shades are drawn, the solar heat gain is attenuated both by the shading properties of the window and the solar transmittance of the shades. Equation 1 shows the total heat flux into the space across the window alone, and Equation 2 shows the total heat flux into the space across the window and drawn shades.

$$q_{total} = U_{window}\left(T_{amb-}T_{in}\right) + I_{solar} \cdot SHGC_{window} \tag{1}$$

$$q_{total} = \left(U_{window} + \frac{1}{R_{shades}}\right)\left(T_{amb} - T_{in}\right) + I_{solar} \cdot SHGC_{window} \cdot \tau_{solar,shades} \tag{2}$$

In both equations, T_{amb} is the ambient outdoor temperature from the weather service and T_{in} is the indoor space temperature from the thermostat. The only quantity in these two equations that is not directly measured or input by the installer is the incident solar radiation on the window, I_{solar}, which requires a more complex calculation. At a high level, the solar radiation is estimated using the Hay, Davies, Klucher and Reindl (HDKR) anisotropic model, from Duffie and Beckman (2006):

$$I_{solar} = I_{beam}\left(1+\frac{I_{diff}}{I_0}\right)\frac{\cos\theta_i}{\cos\theta_s} + I_{diff}\left(1-\frac{I_{beam}}{I_0}\right)\left(\frac{1+\cos\theta_p}{2}\right)\left[1+\frac{I_{beam}}{I_h}\cdot\sin^3\left(\frac{\theta_p}{2}\right)\right] \quad 3$$

In the HDKR model (equation 3), total incident solar is the sum of a beam solar component (I_{beam}) and a diffuse solar component, I_{diff}. These values are estimated based on the total horizontal radiation, I_h and cloud cover (CC). Also, Θ_i is the angle between the beam solar and the normal to the window plane, Θ_s is the zenith angle of the sun, Θ_p is the zenith angle of the window, which is 90 degrees for vertically-oriented windows. Appendix A can be used as a reference on how to calculate these angles based on the time of day, day of year, and information on the time zone and daylight savings. I_0 is the extraterrestrial irradiance (a function only of day of the year – impacted by earth's distance from the sun).

I_h is estimated as the extraterrestrial irradiance normal to the beam, multiplied by the cosine of the zenith angle of the sun, and further modified by three attenuation terms. A constant attenuation factor of 72% accounts for the absorption of solar radiation by the atmosphere, which lowers the maximum solar heat flux to around 1000 W/m^2. Next, a CC attenuation factor is applied. This relationship helps to map the CC percentage from the weather service to the assumed impact of total horizontal radiation. The relationship is assumed to be linear, with an attenuation factor of 1.0 for clear skies (CC = 0) and an attenuation factor of 0.1 for cloudy skies (CC=100). A final attenuation factor accounts for additional atmospheric attenuation of solar radiation that occurs at low solar angles (around sunrise and sunset) due to the additional distance through the atmosphere that the light must travel through. This requires calculation of a term called "air mass" (AM)), (Karsten and Young 1989), using the following relationship:

$$AirMassAttenuation = -0.325\ln(AM) + 1.085 \quad 4$$

In summary,

$$I_h = I_{0,norm}\cos\theta_s \cdot 0.72 \cdot CloudCoverAttenuation \cdot AirMassAttenuation \quad 5$$

I_h is disaggregated from I_{diff} using the following correlation from Erbs, et al.

$$\frac{I_{diff}}{I_h} = \left\{\begin{array}{ll} 1.0 - 0.09k_T & 0.22 > k_T \\ 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4 & 0.22 \le k_T \le 0.75 \\ 0.165 & 0.75 < k_T \end{array}\right\} \quad 6$$

Where k_T is a sky clearness index, defined as

$$k_T = \frac{I_h}{I_{0,norm}\cos\theta_s} \quad 7$$

The beam solar radiation I_{beam} is the total horizontal radiation, minus the diffuse radiation.

D.2 Heating and Cooling Preferences

The preferences for heating (choosing the shading option that promotes the highest window heat gain) and cooling (choosing the shading option that promotes the lowest window heat gain/ highest heat loss) are determined strategically based on the thermostat's mode and the time of day relative to the time of the anticipated high or low temperature. The strategy is determined as follows based on these sets of cases:

1. When the time of day is after 5 AM., but prior to 3 hours before sunset (time of anticipated high temperature)
   - Cooling mode: In cooling mode, the preference will almost always be to cool. The lone exception is when the thermostat temperature is less than the heating setpoint and the forecast high temperature is also below the heating setpoint. In this case, the thermostat may be considered to be inappropriately set to cooling mode, and a preference for heat is used instead.
   - Heating mode: In heating mode, the preference will almost always be to heat. The lone exception is when the thermostat temperature is above the cooling setpoint and the forecast high temperature is also above the cooling setpoint. In this case, the thermostat may be considered to be inappropriately set to heating mode, and a preference for cooling is used instead.
   - Auto mode: In auto mode, there are several scenarios, which are described below:
     i. Preference for heat if
        - space temp is lower than heating setpoint
        - space temp is in-between heating and cooling setpoint and forecast high is below cooling setpoint

     ii. Preference for cooling if
        - space temp is at or above cooling setpoint
        - space temp is in-between heating and cooling setpoint and forecast high is at or above cooling setpoint
2. When the time of day is after 3 hours before sunset (time of anticipated high temperature), but prior to 5 AM (time of anticipated low temperature)
   - Cooling mode: In cooling mode, the preference will almost always be to cool. The lone exception is when the thermostat temperature is less than the heating setpoint and the forecast low temperature is also below the heating setpoint. . In this case, the thermostat may be considered to be inappropriately set to cooling mode, and a preference for heat is used instead.
   - Heating mode: In heating mode, the preference will almost always be to heat. The lone exception is when the thermostat temperature is above the cooling setpoint and the forecast low temperature is warmer than the heating setpoint minus 10°F. In this case, the thermostat may be considered to be inappropriately set to heating mode, and a preference for cooling is used instead.
   - Auto mode: In auto mode, there are several scenarios, which are described below:

   iii. Preference for heat if
      - space temp is lower than heating setpoint
      - space temp is in-between heating and cooling setpoint and forecast low is below heating setpoint (minus 10 degrees)

   iv. Preference for cooling if
      - space temp is at or above cooling setpoint

- space temp is in-between heating and forecast low is above heating setpoint (minus 10 degrees)

D.3 References

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