Pacific Northwest
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PNNL-30536

Evaluation of Exterior Shades at PNNL Lab Homes and Occupied Field Sites

Final Report

October 2020

WE Hunt
KA Cort

U.S. DEPARTMENT OF ENERGY

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

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Pacific Northwest National Laboratory
Richland, Washington 99354

Summary

In residential applications, heat transfer through windows accounts for a significant portion of a home's cooling load. Exterior shades are window attachments that can be applied on the exterior-side of windows in a home. Exterior shades can reduce solar heat gain, reduce glare through a window, and improve comfort in the home. To assess the performance of residential exterior shades, the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), Building Technologies Office (BTO) commissioned a series of field studies for exterior fabric shades to be performed by Pacific Northwest National Laboratory (PNNL) during the cooling seasons of 2019 and 2020. This report describes the experimental setup and results of these exterior shade field studies.

PNNL, in collaboration with Lawrence Berkeley National Laboratory (LBNL), evaluated exterior shades at the PNNL Lab Homes and three occupied field sites in Richland, Washington. At the Lab Homes, the energy performance of exterior shades was evaluated in a controlled side-by-side environment. At the occupied field sites, exterior shades were characterized by measuring shade usage, documenting installation practices, and surveying customer perspectives.

At the Lab Homes, the application of exterior shades on three larger west- and south-facing windows yielded cooling HVAC savings of approximately 20% when compared to the Baseline Home, where the same 3 windows were left uncovered. When compared to interior vinyl blinds, exterior shades demonstrated daily HVAC energy savings from 1.0 to 3.2 kWh, which equates to approximately 10% savings for space cooling. The application of exterior shades also facilitated a more comfortable indoor environment, where indoor temperatures in the rooms with exterior shades covering the windows were 2°F to 3°F cooler than the same rooms in the Baseline Home where the windows were covered with vinyl blinds. In a no-cooling test case, the home with exterior shades was 9°F cooler than the home with vinyl blinds on a sunny day where outdoor mid-day temperatures were around 75°F, which suggests that exterior shades could be an effective measure to control solar gains and improve occupant comfort for homes without mechanical cooling in mild climates.

At three occupied field sites in Richland, Washington, three unique exterior shade applications were investigated. The installation practices and installation costs were documented at each site. Each of the homeowners was surveyed to understand their usage and unique perspectives of exterior shades. In addition, field monitoring was deployed at the occupied field sites to measure shade usage and examine the impacts of exterior shading on the indoor temperature of shaded rooms. The homeowners of all three field sites reported satisfaction with their application of the exterior shades. The homeowners were particularly satisfied with the exterior shade's ability to reduce glare while preserving a view to the outdoors. The homeowners also found the exterior shades to be reliable, easy to use, and provide improved comfort in the indoor space. Improved occupant comfort, in terms of reducing the indoor temperature, was confirmed with field measurements at all three occupied field sites.

The overall results demonstrated that the applications of exterior shades can provide HVAC energy savings and improve the comfort of homes during the cooling season. In particular, the Lab Homes results demonstrated energy savings could be achieved with exterior shades deployed on the three west- and south-facing windows.

Acknowledgments

The authors thank Springs Window Fashions, which donated the exterior shades and controllers for the Lab Homes experiments. We thank Rainier Industries and Northwest Shade Company, which provided consultation and discounted exterior shades for the field studies. We thank John Gant at Glen Raven, Inc., and Max Sebrects and Gilles Vanpoucke at Renson, who provided consultation on exterior shade products, configurations, and the selection of field sites. From PNNL we thank Jaime Kolln who helped instrument and manage both the Lab Homes testing and field site setups and Edward Louie who helped with data collection and provided a peer review for this report.

This work is supported by the Buildings Technology Office of the U.S. Department of Energy (DOE) and special thanks goes to Marc LaFrance at DOE for guiding this research. We also thank Charlie Curcija at Lawrence Berkeley National Laboratory and Mahabir Bhandari at Oak Ridge National Laboratory for their review and consultation throughout the experimental and study design process.

Acronyms and Abbreviations

kW	kilowatt(s)
kWh	kilowatt-hour(s)
HVAC	heating, ventilation, and air-conditioning
SEER	seasonal energy efficiency ratio
SHGC	solar heat gain coefficient
PNNL	Pacific Northwest National Laboratory

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1.0 Introduction

Window attachments represent a wide range of products that are commonly used to control glare, provide privacy, and offer home aesthetics. Fabric exterior shades are a type of window attachment designed for the outside of windows, which preserve an outdoor view when closed and can be operated remotely. Exterior shades can be utilized to reduce the solar heat gain through windows and can be used to improve occupant comfort in both conditioned and unconditioned homes during the cooling season. To examine the energy savings and comfort implications of exterior shades, DOE commissioned a series of field validation tests at PNNL's Lab Homes facility and in three occupied field sites during the summers of 2019 and 2020.

PNNL evaluated exterior shades at the PNNL Lab Homes and three occupied field sites in Richland, Washington. At the Lab Homes, the energy performance of exterior shades was evaluated in a controlled side-by-side environment. At the occupied field sites, exterior shades were characterized through measured shade use, documentation of installation practices, and surveying customer perspectives. This report describes the experimental setup and results of these exterior shade studies.

The PNNL Lab Homes (one Baseline Home and one Experimental Home) are identical in construction and thermal performance, and each home is equipped with end-use metering and environmental sensors. The Experimental Home was modified to include exterior shades on selected south- and west-facing windows. The energy performance and indoor comfort with exterior shades were evaluated at the Lab Homes during a cooling season. The Lab Homes experiments include three test cases where the performance of exterior shades in the Experimental Home were compared with the Baseline Home, which had no shades, for one test case, and had vinyl blinds covering the targeted windows, for the second test case. A third Lab Homes test case examined the temperature impact from the application of exterior shades in a home without mechanical cooling.

At occupied field sites in Richland, three unique exterior shade applications were examined. The installation practices and costs were documented at each site. Each of the homeowners was surveyed to understand their use and unique perspectives of exterior shades. In addition, field monitoring was used at the occupied field sites to measure shade use and examine indoor temperature impacts of exterior shaded rooms.

2.0 Background

This section includes a technology overview for the application of exterior shades on windows, building characteristics of the PNNL Lab Homes, and previous research conducted at the PNNL Lab Homes for applicable window attachments.

2.1 Technology Overview

Exterior shades refer to shade technologies that are designed to be installed on the outside of buildings. Exterior shades can effectively reduce solar heat gain through the window, which makes this technology primarily a cooling season application. Exterior shade products are commonly installed on outside patios or decks and typically include a mechanical crank, rod, or motor to allow operation from indoors and the most popular products in recent years are those that are raised and lowered via remote control that operates a motor integrated with the shade hardware.

For this study, exterior shades were evaluated on the exterior surface of large west-facing or south-facing windows for residential applications. The general components of the exterior shades evaluated in this study included the cassette, which houses the motor and raised shade; the shade fabric, available in varying colors and levels of openness (that is, the amount of open space in the fabric pattern of the exterior shade); and the track or guide that contains the shade at the desired plane. The visible components of one of the exterior shades evaluated in this study are identified in Figure 1. Exterior shades may include a variety of optional accessories such as an integrated solar panel for powering the motor and a wind sensor that raises the shade during excessive wind speeds.

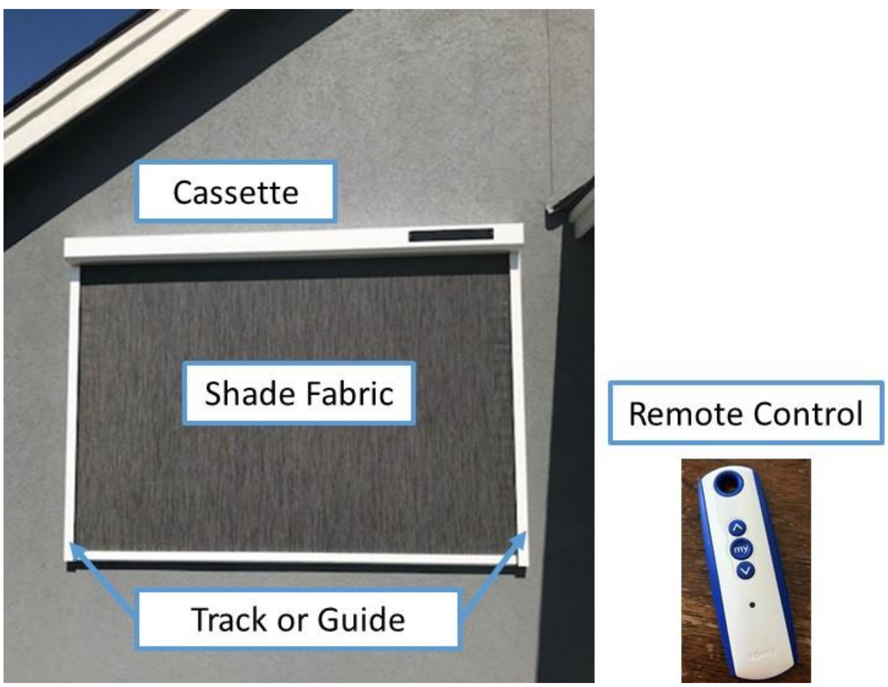


Figure 1. Example of Exterior Shade Technology for Window Application

2.2 PNNL Lab Homes

The side-by-side PNNL Lab Homes (Figure 2) are located on the PNNL campus in Richland. One home serves as the Experimental Lab Home, the other as the Baseline Lab Home. The Experimental Lab Home is used to evaluate emerging residential technologies and control strategies, while the Baseline Lab Home serves as an untouched baseline comparison. This research platform is used to represent existing U.S single-family residences. Each home contains a central, 13 seasonal energy efficiency ratio (SEER) air-conditioner with comparable ductwork. The central air-conditioner of each home is controlled by an *ecobee4* thermostat located in the home's hallway. Envelope air leakage and duct leakage are regularly evaluated at the Lab Homes to ensure comparable levels exist in each home. The Lab Homes contain nine double-pane clear glass windows including three south-facing windows and two west-facing windows. One of the south-facing windows and one of the west-facing windows are sliding glass doors. The performance rating of the windows installed in the Lab Homes is provided in Table 1.

Figure 2. Side-by-Side PNNL Lab Homes

Table 1. Performance Characteristics of the Lab Home Windows

Value	Windows in Lab Homes	
	Windows	Patio Doors
U-factor (Btu/hr-ft^2-°F)	0.68	0.66
Solar heat gain coefficient	0.7	0.66
Visible transmittance	0.73	0.71

2.3 Prior Window Attachment Research at Lab Homes

Previous window attachment research at the PNNL Lab Homes has included the application of interior and exterior storm window attachments (Knox and Widder 2014; Petersen et al. 2015) and interior double-cell and triple-cell cellular shades (Petersen et al. 2016; Cort et al. 2018). Each of these window attachment studies included all nine windows of the Lab Homes. In addition, each of the studies included internal load simulation to best represent the typical use of space cooling at the Lab Homes. Although the application of the storm windows significantly affects the overall insulating (e.g., U-factor) performance of the window, these window attachments do not shade the window and have only a modest impact on the solar heat gain coefficient (SHGC) and visible transmittance; thus, the effect of the insulating cellular shades on the use of heating, ventilation, and air-conditioning (HVAC) is more comparable to how the application of exterior shades affects HVAC operation. When compared to interior vinyl blinds, the evaluated interior double-cell cellular shades demonstrated an average savings of 13.3% for space cooling (Cort et al. 2018), while the evaluated triple-cell cellular shades demonstrated an average savings of 16.6% for space cooling (Petersen et al. 2016). The exterior shades study focused on three south- or west-facing windows at the Lab Homes, and the experimental design of the exterior shades study did not include internal load simulation. Although there are fundamental differences between the exterior shades study and previous studies, previous research can be used as a point of reference in examining the results of the exterior shades at the PNNL Lab Homes.

3.0 Exterior Shades Evaluation at PNNL Lab Homes

The experimental setup, test plan, and results for the exterior shades evaluation at the PNNL Lab Homes are provided in this section.

3.1 Experimental Setup

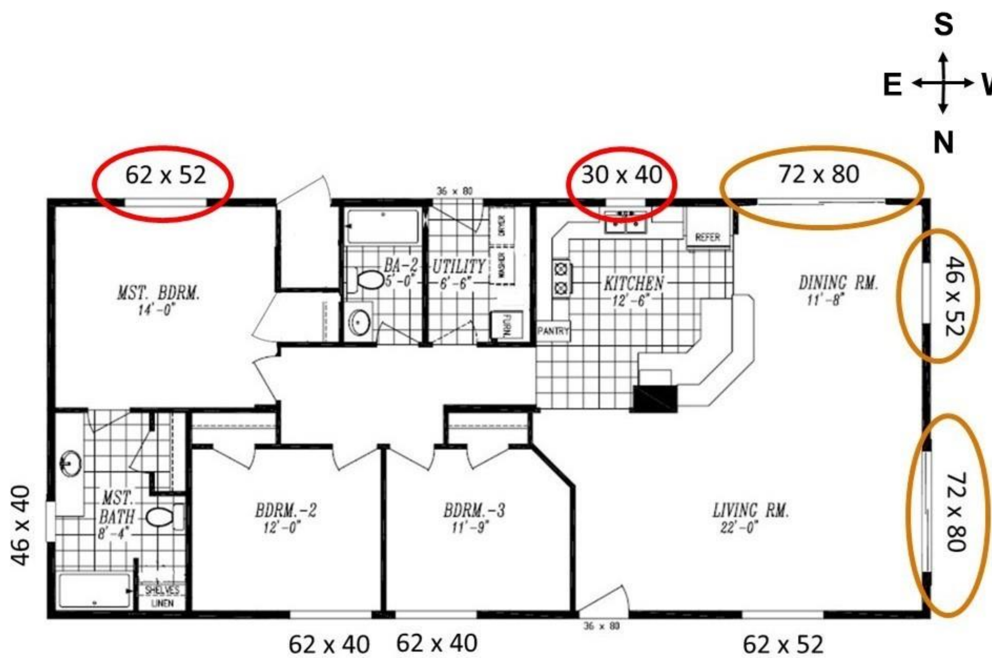
The evaluation of exterior shades occurred at the PNNL Lab Homes between June and September 2019. This section describes the experimental setup at the Lab Homes.

3.1.1 Exterior Shade Application

The focal point for the assessment of exterior shades at the PNNL Lab Homes was three windows located in the adjoined dining and living room area of each home. The three windows included a south-facing sliding door, a west-facing window, and a west-facing sliding door. Because of their size and orientation, these three windows are significant contributors to the overall fenestration load at the homes. **Focal Point of Study: Dining/Living Room Windows**

Remaining South-facing Windows

Figure 3 provides a layout of the Lab Homes, the location of the key windows for this study, and the window sizes. At the Experimental Lab Home, exterior shades were installed on the three identified windows in the dining and living room area. During experimental testing, the Baseline Lab Home operated with either interior vinyl blinds or no shading for the three identified windows in the dining and living room area. For all test cases at both Lab Homes, interior vinyl blinds were used on the two remaining south-facing windows, located in the master bedroom and kitchen. This overall experimental strategy allowed for a focused comparison of exterior shades to interior vinyl blinds and a comparison of exterior shades to no shading at the Lab Homes.



Focal Point of Study: Dining/Living Room Windows
Remaining South-facing Windows

Figure 3. Lab Home Layout and Targeted Windows for Exterior Shades Study

The exterior shades installed at the Lab Homes were black in color with a manufacturer-designed with a 1% openness factor (which reflects the percentage of open space in the fabric pattern). The exterior shades package consisted of a cassette, which was mounted above each window, and guide cables, which were attached to the cassette and below each window. The exterior shades at the Lab Homes were motorized, remotely controlled, and had a wind sensor. The window sensor was set to automatically lift the shades if excessive wind speeds were present. Figure 4 provides an exterior view of the Experimental Lab Home with the installed exterior shades. The top photo shows the exterior shades in the raised position, while the bottom photo shows the exterior shades in the lowered position. As seen in the bottom photo of Figure 4, there was minimal visibility through the exterior shades from an outside to inside perspective.

Figure 4. Exterior Home View of Exterior Shades at PNNL Lab Homes

Figure 5 provides an interior view from the living room area with the exterior shades closed at the Experimental Lab Home. As seen in Figure 5, there was substantial visibility through the exterior shades from the inside to the outside, particularly when sunlight was present.

Figure 5. View Outside during Sunlight with Exterior Shade Closed at Lab Home

Interior vinyl blinds were used on certain windows and during certain test cases at the Lab Homes. The interior vinyl blinds for windows were horizontally slatted, while the interior blinds for the sliding doors were vertically slatted.

The instrumentation packaged used for this study was primarily intended to allow for a comparison of the air-conditioner's energy consumption between experimental test cases. Table 2 provides a summary of the experimental measurements, monitoring method, collected data, and application of data. The instrumentation at the Lab Homes consisted of HVAC energy consumption, interior space temperatures, outdoor temperature and solar irradiance, and window surface temperatures. Figure 6 provides an example of the window surface temperature measurement at the approximate center of the glass.

Table 2. Instrumentation used at the Lab Homes

Measurement	Monitoring Method	Monitored Variables	Data Application
HVAC Energy Consumption	Panel Metering	kWh, kW, amps, volts	Comparison of energy consumption for test cases
Interior Space Temperature	13 ceiling-hung thermocouples; 2 mean radiant temperature sensors	Temperature (°F)	Evaluate interior temperature. Support energy comparison.

Measurement	Monitoring Method	Monitored Variables	Data Application
Outdoor Temperature	Packaged Meteorological Station (includes Thermistor)	Temperature (°F)	Support energy consumption comparison.
Outdoor Solar Irradiance	Packaged Meteorological Station (includes Horizontal Pyranometer)	Irradiance (W/m^2)	Support energy consumption comparison.
Window Surface Temperatures	22 thermocouples (2 per window interior/exterior center of glass)	Temperature (°F)	Investigate window surface temperatures.

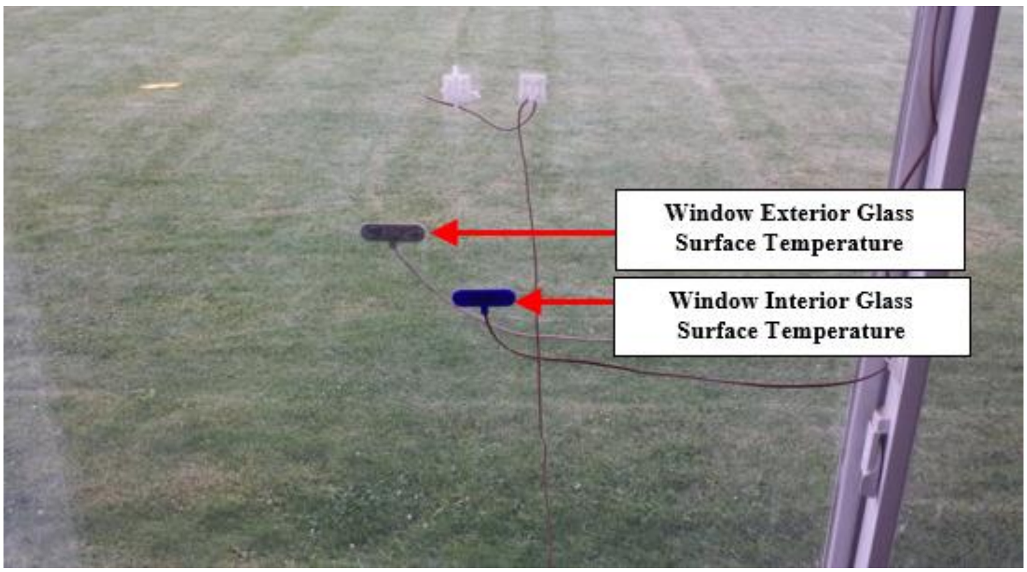


Figure 6. Example of Window Surface Temperature Measurements

3.1.2 Test Plan

This section describes the baselining approach for the study and the experimental test cases for the assessment of energy savings with exterior shades installed at the PNNL Lab Homes.

3.1.2.1 Baselining

Baselining refers to the method of comparing the performance of the two Lab Homes under identical configurations. For this study, baselining was conducted with the described instrumentation and no shading on the three focal windows, located in the dining and living room area of the Lab Homes. Identical interior vinyl blinds were used on the two remaining south-facing windows of each Lab Home during the baselining period. The side-by-side baselining period demonstrated an average difference of 4.3% for air-conditioning energy consumption at comparable indoor temperatures. This offset was factored into the analysis of the experimental results shown in the *Results* section of this report.

3.1.2.2 Test Cases

The experimental test plan for the assessment of exterior shades consisted of three test cases, as listed in Table 3. Test Case 1 provided an energy performance comparison of exterior shades to interior vinyl blinds for the selected application, while Test Case 2 provided an energy performance comparison of exterior shades to no shading. Test Cases 1 and 2 were each conducted at the Lab Homes for over seven days of side-by-side Lab Home data collection. Finally, Test Case 3 provided a comparison of indoor temperature for a day in which the outdoor conditions were mild (outdoor average temperature of 62°F). Test Case 3 was conducted for a single day of data collection. Figure 7 and Figure 8 provide detailed schematics of each Lab Home and window for each of the three test cases. Figure 7 provides the Lab Homes configuration for Test Case 1, while Figure 8 provides the configuration for Test Cases 2 and 3.

Table 3. Test Cases for Exterior Shades at Lab Homes

Test Case	Baseline Lab Home (3 Focal Windows of Study)	Experimental Lab Home (3 Focal Windows of Study)	HVAC Operation
1	Vinyl interior blinds closed	Exterior shades closed	ON; Cool to 75°F
2	No window shading	Exterior shades closed	ON; Cool to 75°F
3	No window shading	Exterior shades closed	OFF

During Test Cases 1 and 2, the thermostat in each Lab Home was set to cool to a temperature of 75°F. Each thermostat controlled an identical 13 SEER central air-conditioner. The Lab Homes can provide simulated internal loads (occupancy and appliance use); however, this capability can be curtailed based on the experimental design of a project. For the assessment of exterior shades, internal load simulation was assumed to have a negligible impact on the difference in air-conditioning energy consumption between the Experimental and Baseline Lab Home. As a result, the internal load simulation was not operated during the assessment of exterior shades at the Lab Homes.

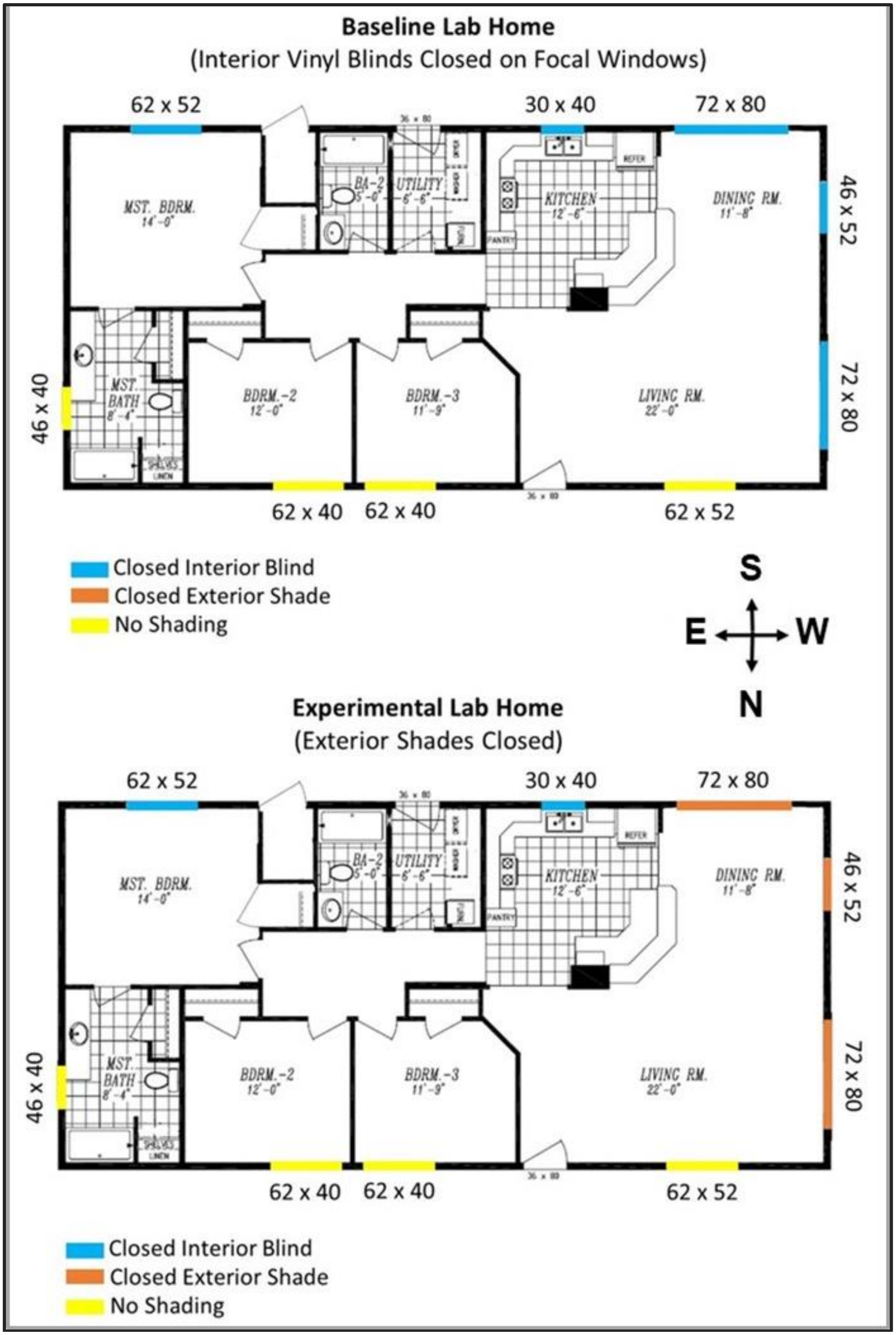


Figure 7. Lab Home Configurations for Test Case 1

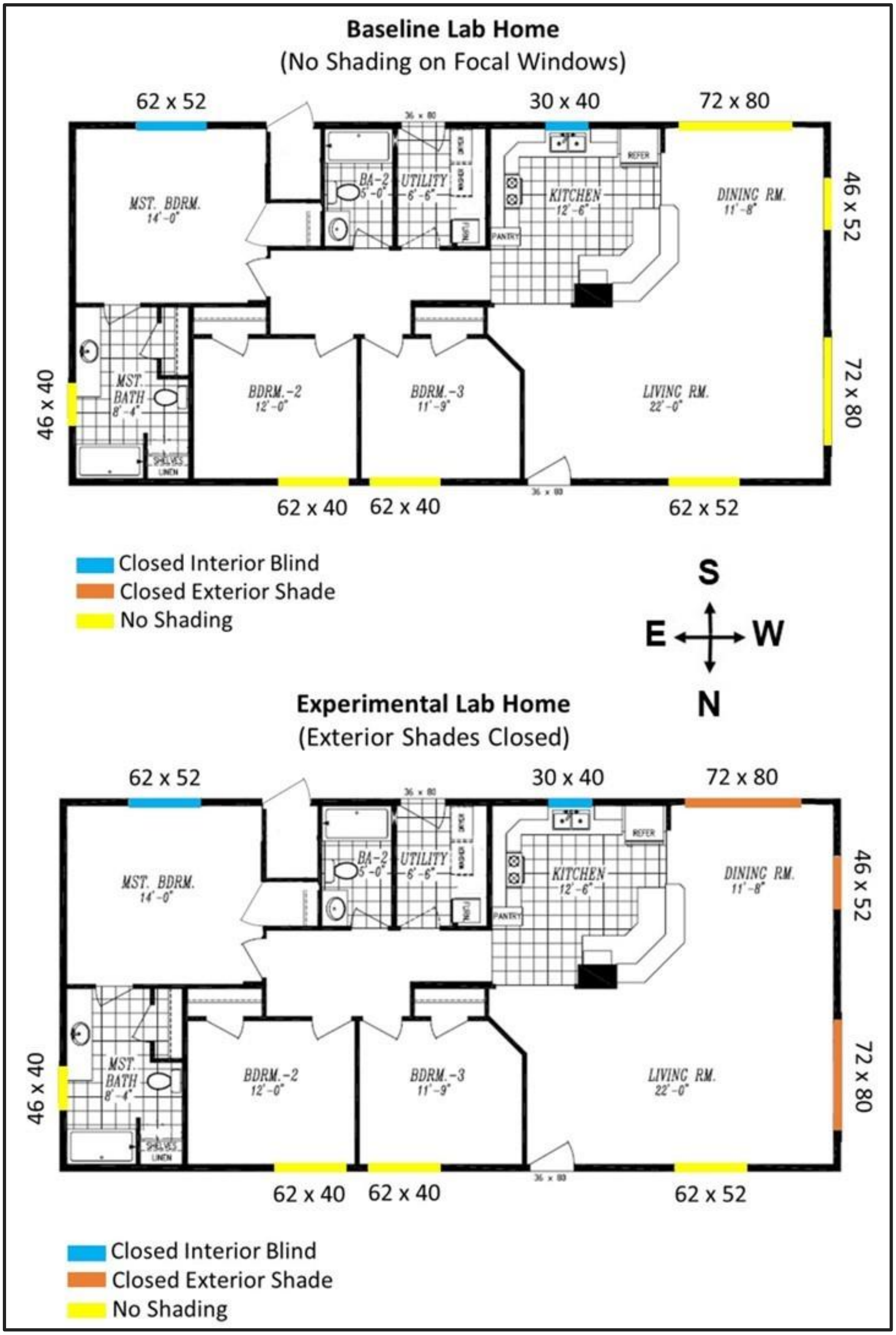


Figure 8. Lab Home Configurations for Test Cases 2 and 3

3.2 Results

This section provides the experimental results of the assessment of exterior shades at the PNNL Lab Homes. Results are categorized for each of the three test cases described in Section 3.1.2 of this report.

3.2.1 Test Case 1

For Test Case 1, the daily air-conditioning energy consumption of the Experimental Lab Home with exterior shades and the Baseline Lab Home with interior vinyl blinds was compared. Figure 9 provides the air-conditioning energy savings with exterior shades for each day of Test Case 1. In Figure 9, daily HVAC energy savings are shown as a function of average daily outdoor solar irradiance and outdoor air temperature. The daily air-conditioning energy savings for Test Case 1 ranged from 1.0 to 3.2 kWh, as a function of the outdoor conditions. For the PNNL Lab Homes, these results equate to approximately a 10% energy savings for air-conditioning when including internal loads. The outdoor irradiance and temperature varied over the test days for Test Case 1, which resulted in the range of HVAC savings. Increased outdoor solar irradiance resulted in higher energy savings for the exterior shades application.

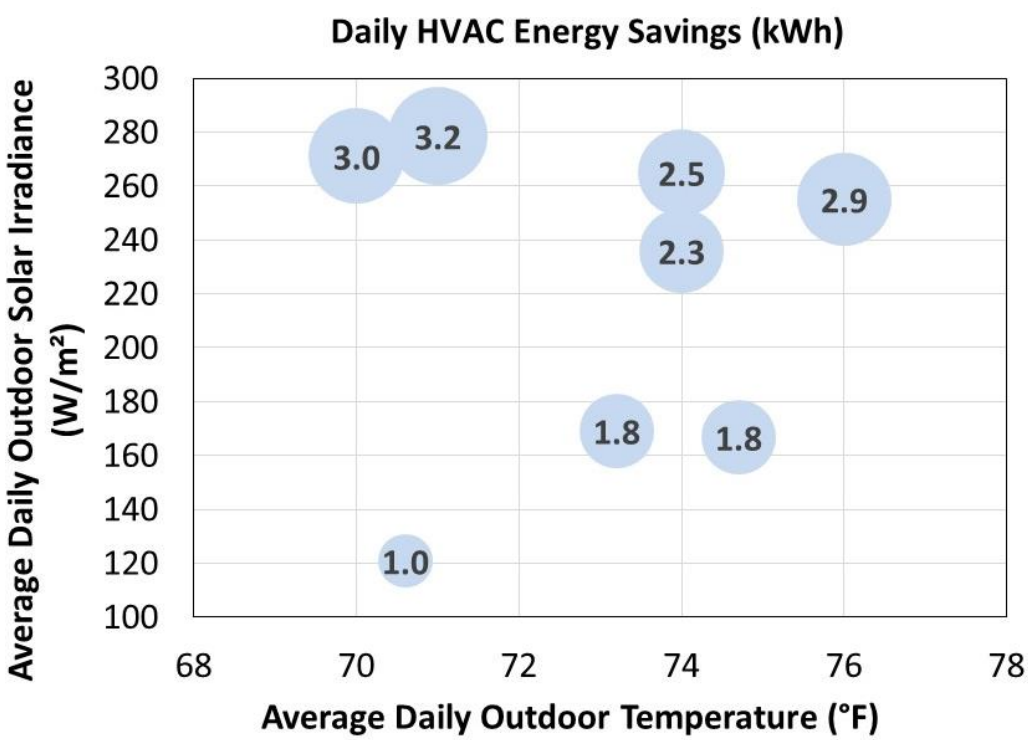


Figure 9. Air-Conditioning Energy Savings with Exterior Shades Compared to Interior Blinds

Occupant comfort was examined for Test Case 1 by taking a mean radiant temperature measurement, centrally located in the dining room of each Lab Home. Figure 10 provides daily average, mean radiant temperatures over a continuous five-day period during Test Case 1 for each Lab Home. The dining room's mean radiant temperature in the Baseline Lab Home with interior vinyl blinds was approximately 2°F to 3°F warmer than it was in the Experimental Lab Home with exterior shades over the sample of test days.

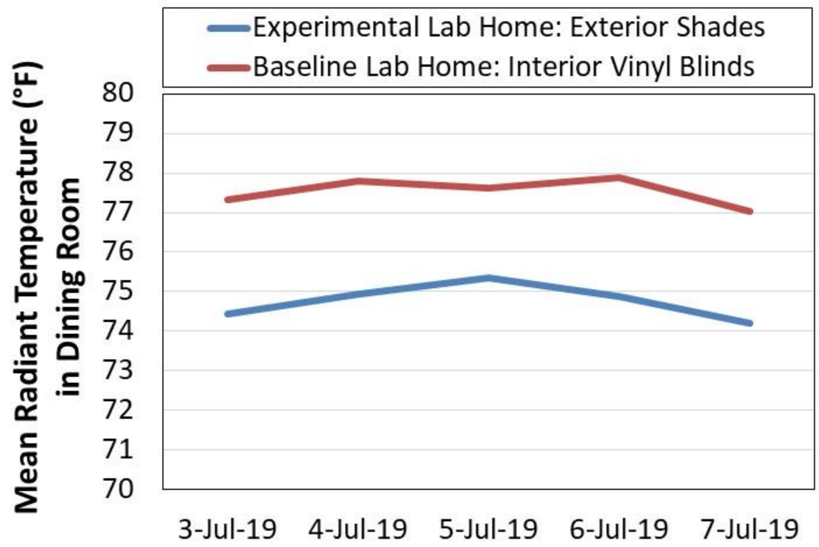


Figure 10. Comparison of Mean Radiant Temperature in the Dining Room

Heat transfer through the dining room sliding door was examined by taking a center-of-glass, interior surface temperature measurement. Figure 11 provides daily average, interior window surface temperatures over a continuous five-day period during Test Case 1 for each Lab Home. The dining room slider's interior window surface for the Baseline Lab Home with interior vinyl blinds was approximately 2°F to 4°F warmer than that of the Experimental Lab Home with exterior shades over the sample of test days.

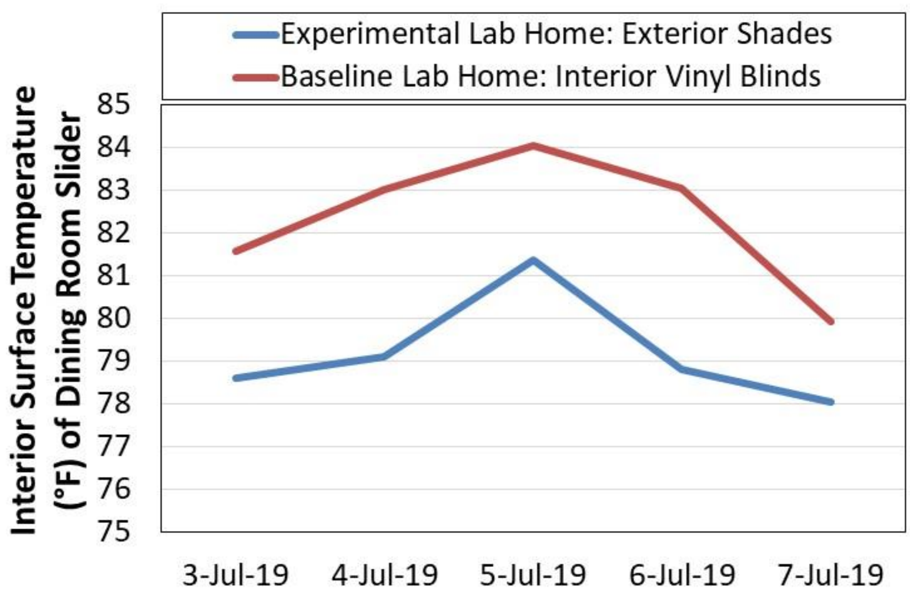


Figure 11. Comparison of the Window Surface Temperature of Dining Room Sliders

3.2.2 Test Case 2

For Test Case 2, the daily air-conditioning energy consumption of the Experimental Lab Home with exterior shades and the Baseline Lab Home with no shading was compared. Figure 12 provides the air-conditioning energy savings for each day of Test Case 2 as a function of the average daily outdoor solar irradiance. For an additional perspective, Figure 12 also provides results for each day for Test Case 1, when interior vinyl blinds were used in the Baseline Lab Home. The HVAC energy savings for Test Case 2 ranged from 2.4 to 5.2 kWh, as a function of the outdoor conditions. For the PNNL Lab Homes, these results equate to approximately a 20% energy savings for air-conditioning when including internal cooling loads.

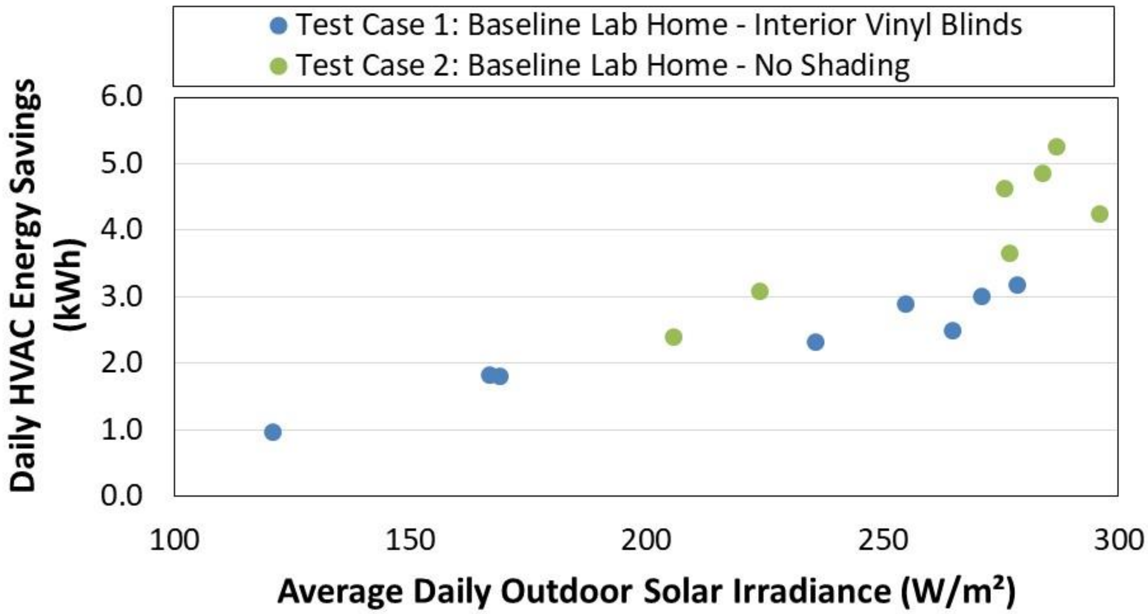


Figure 12. Air-Conditioning Energy Savings with Exterior Shades Compared to Interior Blinds and No Shading

3.2.3 Test Case 3

For Test Case 3, the indoor home temperatures were examined for the Experimental Lab Home with exterior shades, the Baseline Lab Home with no shading, and HVAC operation OFF. Test Case 3 was conducted on a day of mild outdoor temperature and that featured a daily average of 62°F. Figure 13 provides the dining room indoor temperatures and outdoor conditions over the course of one day for Test Case 3. The indoor temperature in this case refers to an interior space temperature measurement taken in the center of the dining room. During the early morning hours (i.e., before the sun rose) of the test day, the dining room indoor temperatures were following a similar trend in the Lab Homes. As the sun rose, a deviation in the indoor temperature curves begins to occur. At the pinnacle of the indoor temperature curves, the Baseline Lab Home (no shading) is approximately 9°F warmer than the Experimental Lab Home (exterior shades closed). This test case demonstrates how the use of window attachments (e.g., exterior shades) in mild climates limits the solar heat gain through windows and potentially offsets the need for space cooling.

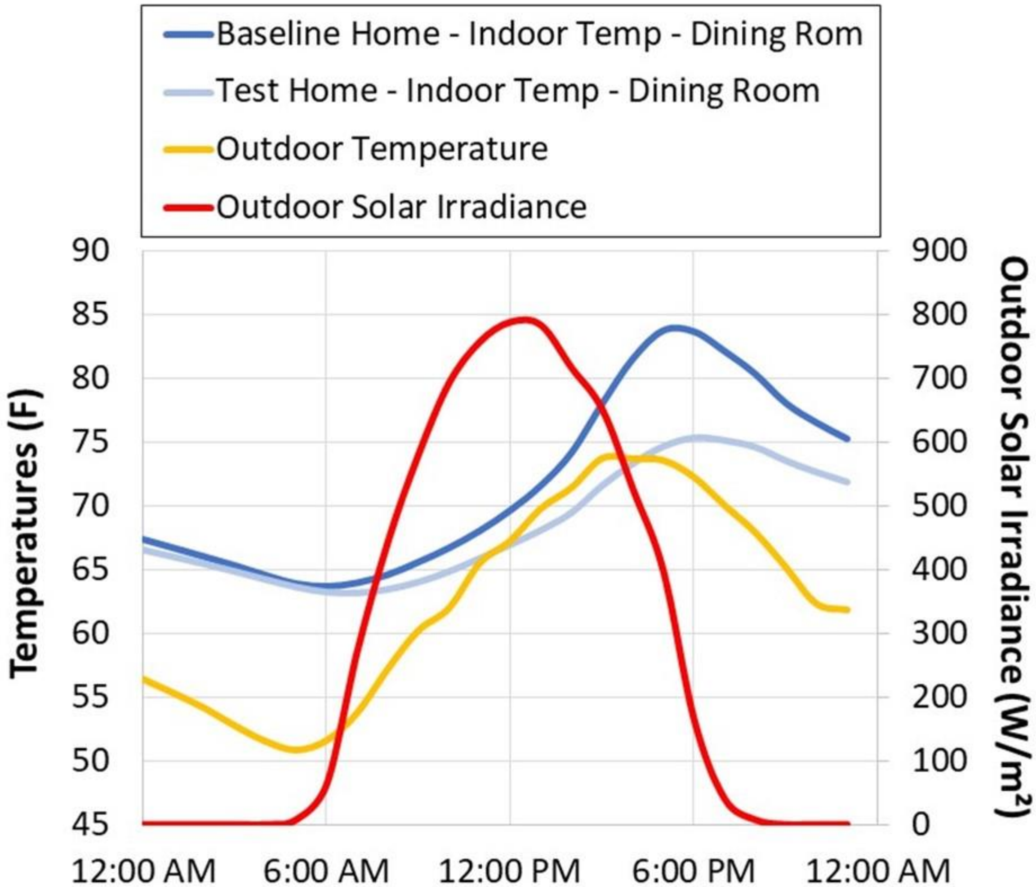


Figure 13. Interior Home and Outdoor Conditions during a Mild Temperature Day

3.2.4 Summary

In the two test cases for which HVAC cooling was operational, the application of the three exterior shade window attachments yielded cooling HVAC savings. When compared to interior vinyl blinds, exterior shades demonstrated daily HVAC energy savings from 1.0 to 3.2 kWh, which equates to approximately 10% HVAC savings for air-conditioning when including internal loads. The HVAC energy savings for Test Case 2, for which the Experimental Lab Home was shaded with exterior shades and the Baseline Home remained unshaded, ranged from 2.4 to 5.2 kWh, which equates to approximately a 20% energy savings for air-conditioning when including internal loads. The energy savings with exterior shades for space cooling is comparable to double-cell cellular shades evaluated in previous studies at the PNNL Lab Homes.

Occupant comfort was examined for Test Case 1, which compared the mean radiant temperature measurements near the dining room of each Lab Home. The dining room's mean radiant temperature in the Baseline Lab Home with interior vinyl blinds was approximately 2°F to 3°F warmer than it was in the Experimental Lab Home with exterior shades during the sample of test days. For Test Case 3, occupant comfort was compared for the Lab Homes with and without the use of shades when no HVAC was employed in the homes. For this experiment, the results indicate that the Baseline Lab Home (no shading) is approximately 9°F warmer than the Experimental Lab Home (exterior shades closed), which demonstrates how the use of window attachments, such as exterior shades, can effectively limit solar heat gain and improve comfort and potentially offset the need for air-conditioning in mild climates.

The overall results demonstrated that the Lab Home's application of exterior shades provided cooling savings and improved indoor comfort. In particular, the Lab Homes configuration and experiments demonstrated that these savings could be achieved with exterior shades on the three larger west- and south-facing windows.

4.0 Exterior Shades Evaluation at Occupied Field Sites

Although the experimental Lab Homes study provides a precise measurement of the HVAC energy savings and comfort implications by measuring temperatures throughout the home, these experiments are not able to capture the human experience of certain attributes such as views through the windows, privacy, or aesthetics. In addition, the controlled Lab Homes cannot capture information about how the home occupant interacts with or operates the shades. To further evaluate and characterize factors such as glare and overall comfort effects on the people who occupy the home, additional field evaluations of exterior shades were performed during the summer of 2020 in three occupied homes.

Three field site homes were selected for the study that included large west- and/or south-facing windows where the effects of solar heat gain would be most pronounced. In addition to the window size and orientation, a combination of new and existing homes were selected that had varying levels of shade and differing views to see examine some of the factors that could affect the user experience and how the product was used. For each site, the procurement and installation of the shades was examined relative to differing criteria to observe the ease with which the product could be acquired and installed for a given situation.

4.1 Exterior Shade Applications

Three occupied field sites in the Richland area were used to investigate the procurement, installation, homeowner perspective, and use of exterior shades. Table 4 provides an overview of the exterior shade applications at the three field sites. The applications consisted of mix of window quantities, window styles, and window orientations. At Field Site 1, two matching, west-facing windows were targeted for an exterior shade application. At Field Site 2, a fixed, south-facing window in the home's dining and kitchen area was selected. At Field Site 3, a west-facing sliding glass door on the home's dining room was identified for an exterior shade application. For all three applications, the exterior shades were the only installed shading on the targeted home windows.

Table 4. Exterior Shade Application for Occupied Field Sites

Field Site	Window Quantity	Interior Room of Window(s)	Window(s) Style	Orientation of Window(s)
1	2	Dining and Bedroom	Partially Operable Window	West-facing
2	1	Kitchen / Dining	Fixed Window	South-facing
3	1	Kitchen / Dining	Sliding Glass Door	West-facing

At each occupied field site, a unique exterior shade was selected and installed for each application. Table 5 provides a summary of the characteristics of the selected exterior shades at each site. Across the sites, the selected exterior shades varied in size, openness, color, and the power source for the shade motor. Openness refers to the amount of open space in the fabric pattern of the exterior shade. Exterior shades are commonly available in darker colors because the darker colors make it easier for homeowners to see outside when the exterior shades are closed. Two of the selected exterior shades required a 120V outlet, while one of the selected products contained an integrated solar panel and battery to operate the shade motor. The field application and installed exterior shades at each occupied site are shown in Figure 14 through 16 for Field Sites 1, 2, and 3, respectively.

Table 5. Characteristics of Selected Exterior Shades for the Field Sites

Field Site	Shade Quantity	Shade Dimensions	Openness of Shade	Shade Color	Power Source for Integrated Motor of Shade
1	2	8’8” W x 6’ H	5%	Dark Gray	Integrated Solar Panel and Battery
2	1	10’9” W x 6’7.5” H	5%	Black	External Plug for 120V Outlet
3	1	6’2” W x 7’ H	1%	Black	External Plug for 120V Outlet

Figure 14. Exterior Shade Application at Field Site 1

Figure 15. Exterior Shade Application at Field Site 2

Figure 16. Exterior Shade Application at Field Site 3

4.2 Shade Installations

The procurement channel and exterior shade installer for the three occupied field sites were different. At two of the sites, the exterior shade hardware and installation were procured together through a single vendor. Equipment and installation for Field Site 1 were procured through a local contractor, while a shade manufacturer was used for Field Site 2. Table 6 provides a summary of installation considerations and costs associated with the exterior shades. The approximate costs listed in the table include the exterior shade hardware, remote control, installation of the shades, and provisions for connecting power, if applicable. At Field Site 1, the exterior shades included an integrated solar panel and did not require an external power connection. At Field Site 2, the exterior shades were powered through a 120V plug, and an electrician installed an outdoor electrical outlet at the exterior shade's location. The product details and site requirements at Field Sites 1 and 2 were different, but the approximate cost per installed shade was similar at $2,000. At Field Site 3, the homeowner installed the same exterior shade that had been installed as part of the Lab Homes experiment (see Figure 4) over a similarly sized window as a DIY project.

Table 6. Installation Considerations and Costs of Exterior Shades at Field Sites

Field Site	Shade Procurement	Professional Installation Included	Cost Considerations	Approximate Cost per Installed Shade
1	Local Contractor	Yes	Integrated solar panel and battery to power motor	$2,000
2	Manufacturer	Yes	Site layout required an electrician to add exterior electrical outlet.	$2,000
3	Distributor	No	Shades were installed by the homeowner.	Donation

The methodology of installing the exterior shade hardware also differed between two sites professionally installed. At Field Site 1, a single installer used a support frame to lift the cassette of the exterior shade to the proper elevation for installation. At Field Site 2, two installers each used a ladder to lift the cassette and exterior shade above the selected window. The installation methodologies for Field Sites 1 and 2 are shown in Figure 17 and Figure 18, respectively.

Figure 17. Installation Approach of Exterior Shades at Field Site 1

Figure 18. Installation Approach of Exterior Shades at Field Site 2

4.3 Homeowner Survey

Each of the three homeowners were surveyed after having functional exterior shades for at least one month. Table 7 provides a list of the questions asked of the homeowners. The questions focus on the use of shades, perceived benefits, ease of use, and reliability.

Table 7. Survey Questions to Capture Homeowners' Perspectives of Exterior Shades

Question Order	Survey Question
1	How often do you adjust (raise/lower) your exterior shades?
2	What is the most common reason for closing your exterior shades?
3	Which feature of exterior shades is most appealing to you?
4	To what extent have you noticed improved comfort with your exterior shade?
5	Compared to other shades or blinds in your house, how much more or less do use the exterior shades?
6	Rate the ease of use of your exterior shades between easy, neutral, and hard.
7	Rate the reliability of your exterior shades between reliable, neutral, and unreliable.

The summary responses to the survey from each of the three homeowners are provided in Table 8. All three of the homeowners mentioned reducing glare as a reason for closing the exterior shade. Figure 19 and Figure 20 provide examples of glare reduction with exterior shading at Field Site 1 and Field Site 3. In addition, all three of the homeowners mentioned the ability to see outside with the shade closed as the most appealing feature of exterior shades. Figure 21 provides a view outside with the exterior shade closed at each of the three sites. The homeowners also found their exterior shades to be reliable, easy to use, and provide improved comfort in the indoor space. One distinguishing factor of the configuration of Field Site 3's installation relative to the other two sites was that the shade was installed from the soffit about 5 inches out from the window to avoid a light fixture and is drawn down with the use of guidewires rather than the side rails used for Field Sites 1 and 2. It was also installed with a wind sensor, which is designed to automatically raise the shade during excessive wind speed. The Field Site 3 homeowner found that the shade would flap in windy conditions and although the wind sensor would automatically raise the shade during windy periods with sustained high wind speed, the sensor did not always trigger the shade to raise during gusty conditions when the direction and velocity of wind changed frequently. Thus, it could be concluded that in windy areas, a close side-mount installation with side rails would be preferable.

Table 8. Summary of Homeowner's Response to Survey

Question Order	Site 1 Responses	Site 2 Responses	Site 3 Responses
1	Once per day	Once per day	Multiple times per day
2	Reduce glare	Energy savings, reduce glare, privacy	Reduce glare
3	Ability to see outside with shade closed	Ability to see outside with shade closed	Ability to see outside with shade closed
4	Significantly more comfortable	Slightly more comfortable	Significantly more comfortable
5	Significantly more use	Similar use	Similar use
6	Easy to use	Easy to use	Easy to use
7	Reliable	Reliable	Reliable

Figure 19. Glare Reduction with Exterior Shade Closed at Field Site 1

Figure 20. Glare Comparison without (left) and with (right) Exterior Shade Closed at Site 3

Figure 21. View Outside during Sunlight with Exterior Shade Closed at Occupied Field Sites

4.4 Field Data Collection and Analysis

At each of the three occupied field sites, a data acquisition platform was deployed to investigate exterior shade usage, shade impact on indoor temperature, and shade impact on the use of HVAC for space cooling. This section describes the field instrumentation and results from the data collection period. Data collection spanned multiple months of Summer 2020.

4.4.1 Data Acquisition

The selected data acquisition system measured outdoor temperature, outdoor solar irradiance, indoor temperature by home's thermostat, indoor temperature in shaded room, outdoor HVAC unit's current, and the position of the shade. The position of the shade was tracked by two contact closures mounted along the track of the exterior shade. Shade position was tracked at Field Sites 1 and 2, but the selected methodology was not conducive for tracking shade position at Field Site 3. All the exterior shades were capable of being stopped in the middle of their track by the remote control, but during the study each of the homeowners was asked to only completely raise or completely lower the exterior shades. Therefore, shade position was tracked and recorded as either open or closed. In addition, Field Site 1 had two identical exterior shades that were raised or lowered simultaneously by a single remote. Figure 22 provides an example of the outdoor-section of the data acquisition station and the contact closure methodology at the occupied field sites.

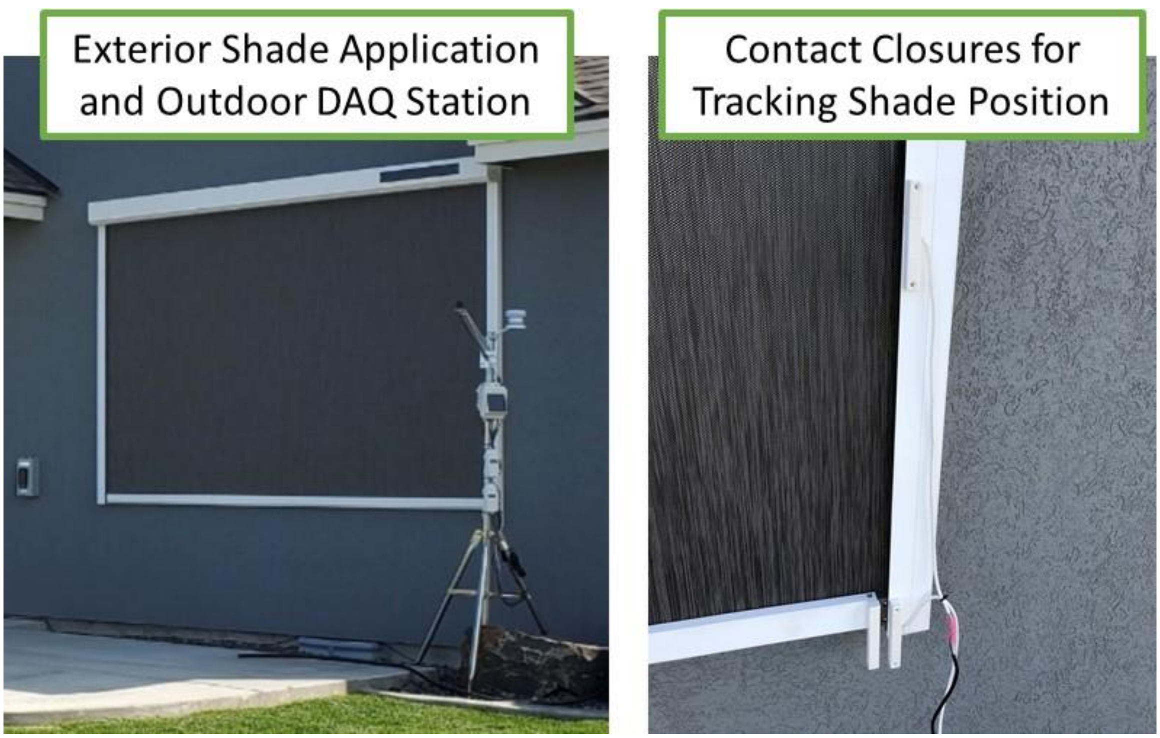


Figure 22. Example of Outdoor Data Acquisition Station and Shade Tracking Methodology

4.4.2 Homeowner Use of Exterior Shades

Throughout the data collection period, all the field sites had consistent home occupancy throughout the day, because all sites had an occupant regularly working from home. The use of shades was examined as the percentage of time that exterior shade(s) were closed. Figure 23 shows the shade use as a daily average over an approximate month of data collection for Field Sites 1 and 2. In Figure 23, it can be observed that day-to-day exterior shade use was sporadic, but the shades were typically adjusted every day (i.e., there were minimal back-to-back days with 0% or 100% use, which would mean the shades were not raised or lowered on those days). The average daily shade use at both sites was around 20% (i.e., exterior shades were closed for approximately 4 to 5 hours per day).

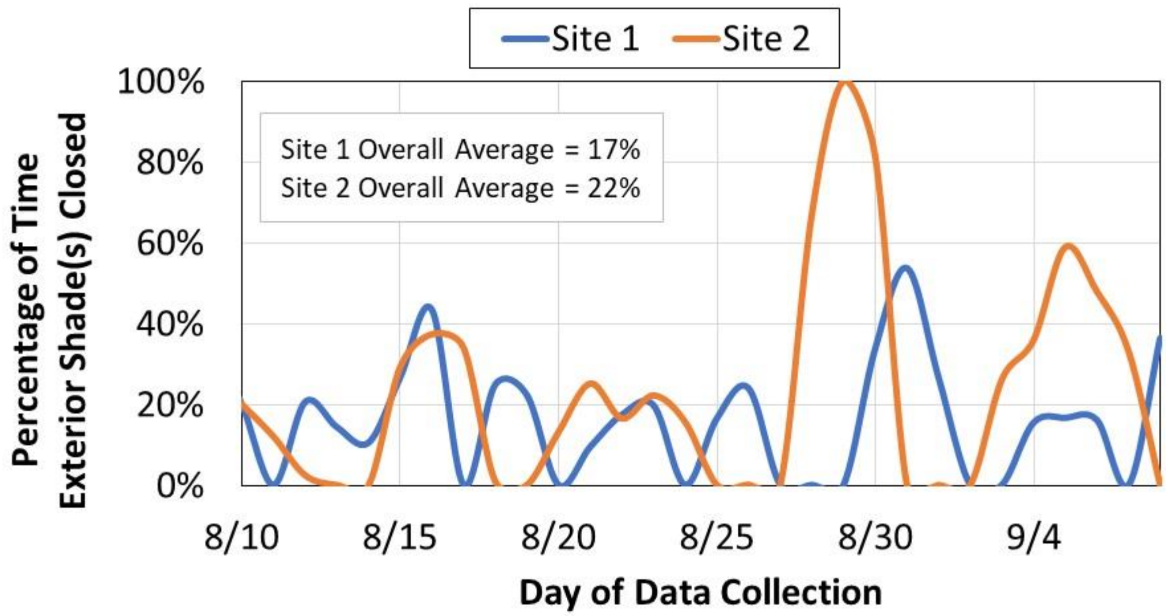


Figure 23. Exterior Shade Use by Daily Average for an Approximate Month of Data Collection

Figure 24 provides the shade use as an aggregated daily profile for Field Sites 1 and 2. Figure 24 is representative of how the exterior shades were used over the course of a typical day. As observed in the figure, the percentage of time the shades were closed sharply increases in the late afternoon, which coincides with peak solar irradiance hours. This observation in the data aligns with the customer survey responses that indicated homeowners were using exterior shades to improve indoor comfort and reduce glare during peak solar irradiance hours. In addition, the homeowners regularly raised the exterior shade when the peak solar irradiance subsided.

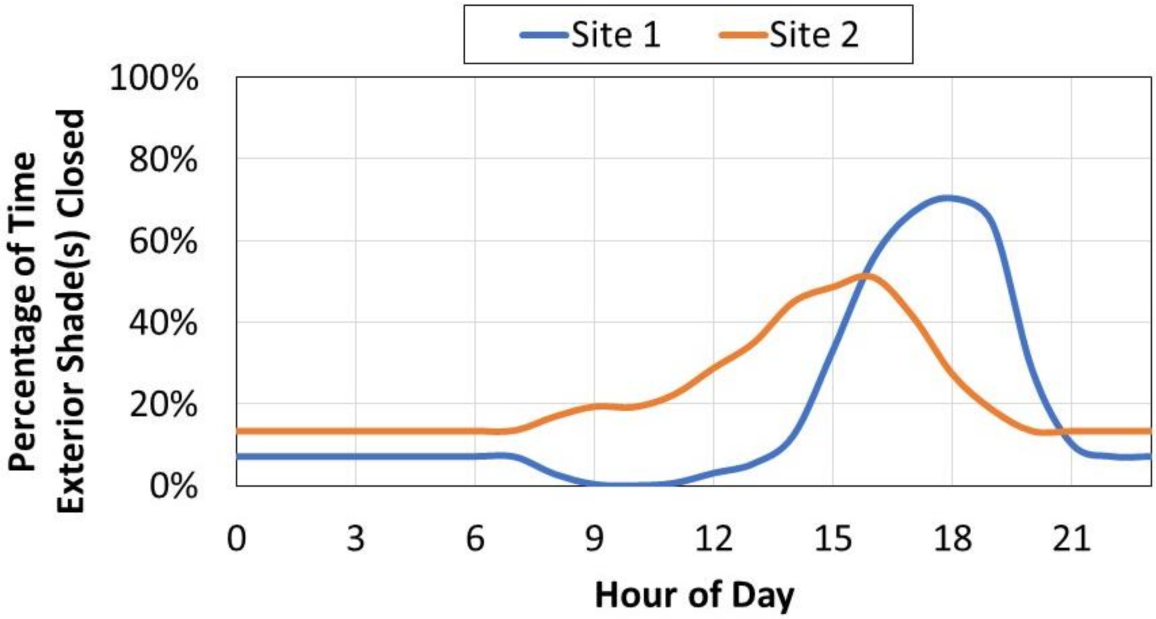


Figure 24. Exterior Shade Use by Hour of the Day

4.4.3 Exterior Shade Impact on Indoor Temperature and Space Cooling

With the ability to track the position of the exterior shades, indoor temperature comparisons could be made between time periods during which the shades were open or closed. At Field Site 1, indoor temperature was monitored at the home's HVAC thermostat, as well as in a bedroom, which used one of the exterior shades. Both the HVAC thermostat and targeted bedroom were located downstairs, which encompassed most of the home's floorspace. At both indoor temperature locations, the temperature sensor was placed in a central location away from windows and exterior walls. Figure 25 provides a comparison of the aggregated indoor temperature profiles for when the exterior shades were either open or closed for the hours of 12 PM to 9 PM. In both cases, the HVAC thermostat indoor temperature was held at approximately 75°F. The outdoor temperature and outdoor solar irradiance profiles were similar for both cases. When the exterior shades were open, the indoor temperature in the bedroom rose approximately 2°F higher than the home's temperature at the HVAC thermostat. When the exterior shades were closed, the bedroom temperature was comparable to the measured indoor temperature at the home's thermostat. This observation from data analysis quantifies the improved occupant comfort gained by using exterior shades at Field Site 1.

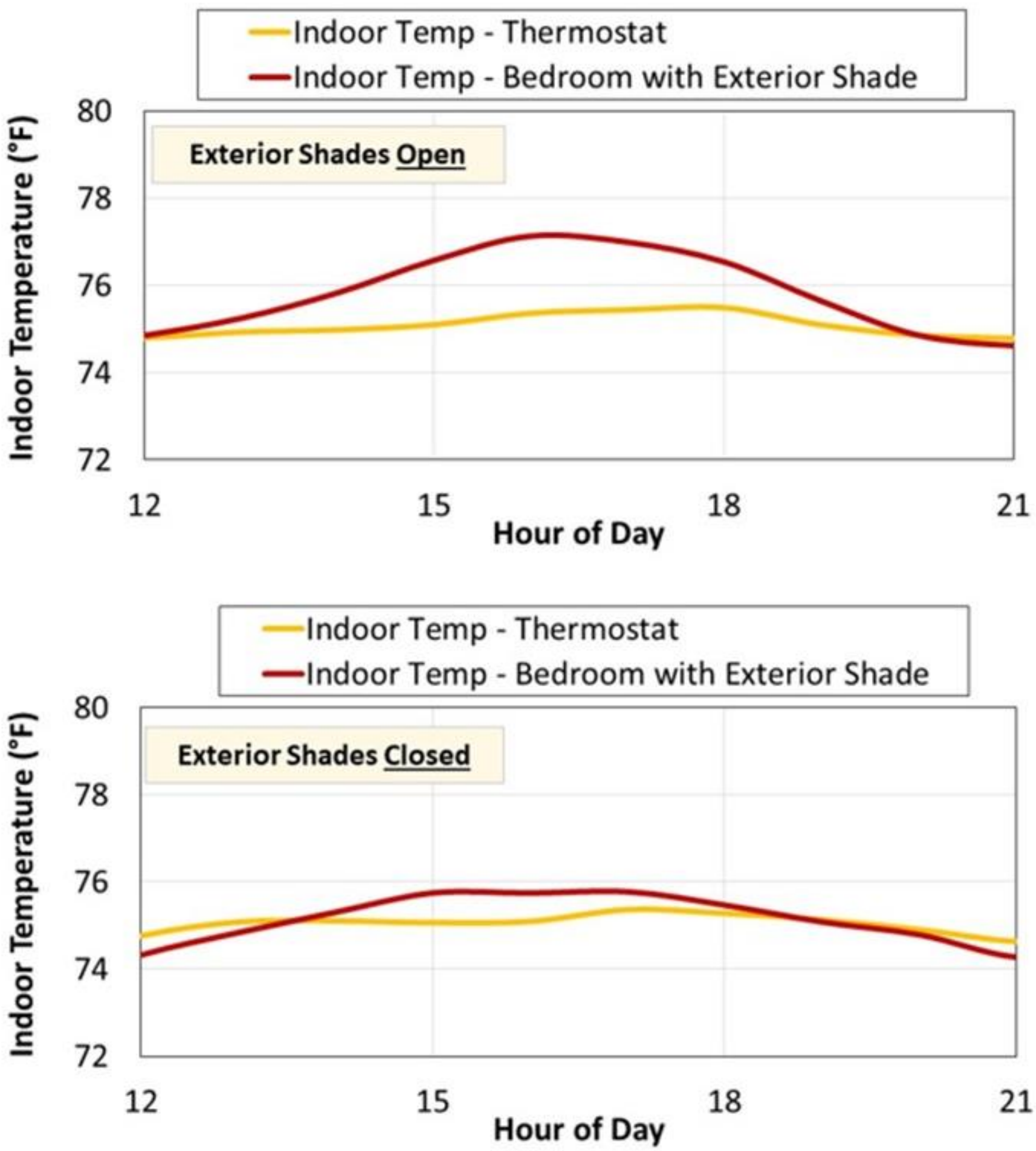


Figure 25. Indoor Temperature Impact of Exterior Shades at Field Site 1

With a similar ability to track shade position at Field Site 2, the impact of the exterior shades on the indoor temperature of the home's dining room was examined. Figure 26 shows the aggregated daily profile of the dining room's indoor temperature for both exterior shade open and closed cases. The outdoor temperature and outdoor solar irradiance profiles were similar for the two indoor temperature data sets compared. At Field Site 2, the HVAC thermostat was located upstairs and was consistent for both cases, while the dining room and associated exterior shade was located downstairs. As shown in the figure, the indoor temperature profile of the dining room with the exterior shade closed provided an average temperature reduction from approximately 0.5°F to 1.0°F across the profile. Use of the home's exterior shade would lead to improved comfort in the associated indoor space.

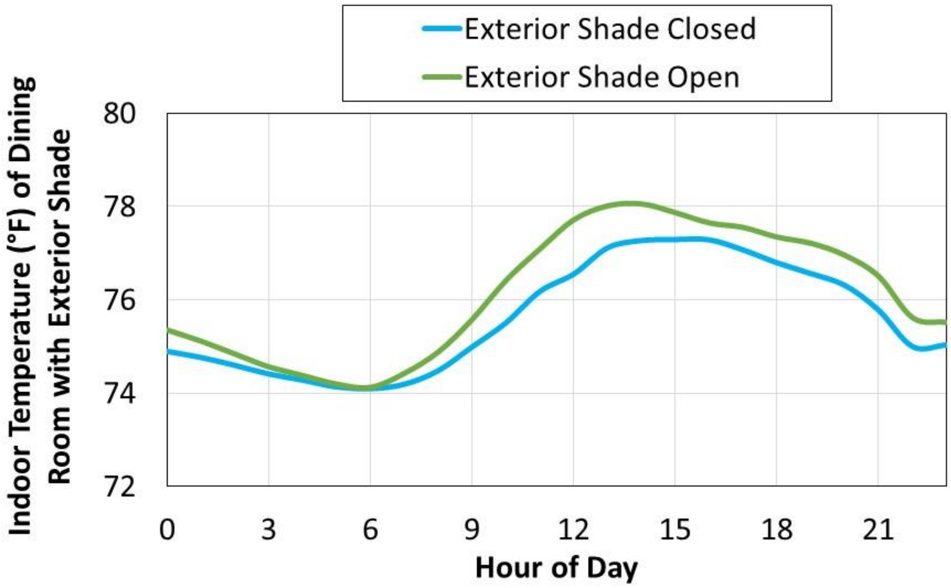


Figure 26. Indoor Temperature Impact of Exterior Shade at Field Site 2

Although the exterior shade position at Field Site 3 was not able to be tracked through field monitoring, the homeowner was able to note their general shade use. The exterior shade at Field Site 3 resided on a sliding glass door in the home's dining room, and that glass door received significant solar irradiance in late afternoon hours. For Field Site 3, Figure 27 provides a comparison of the aggregated indoor temperature in the dining room from 3 PM to 7 PM for a set of days during which the exterior shade was either fully closed or fully open. For both sets of days, the outdoor conditions were similar, and the HVAC thermostat was set at 78°F. For days during which the exterior shade was open, the dining room indoor temperature spiked around 6 PM, and the room was approximately 4°F warmer on average, than days on which the exterior shade was closed.

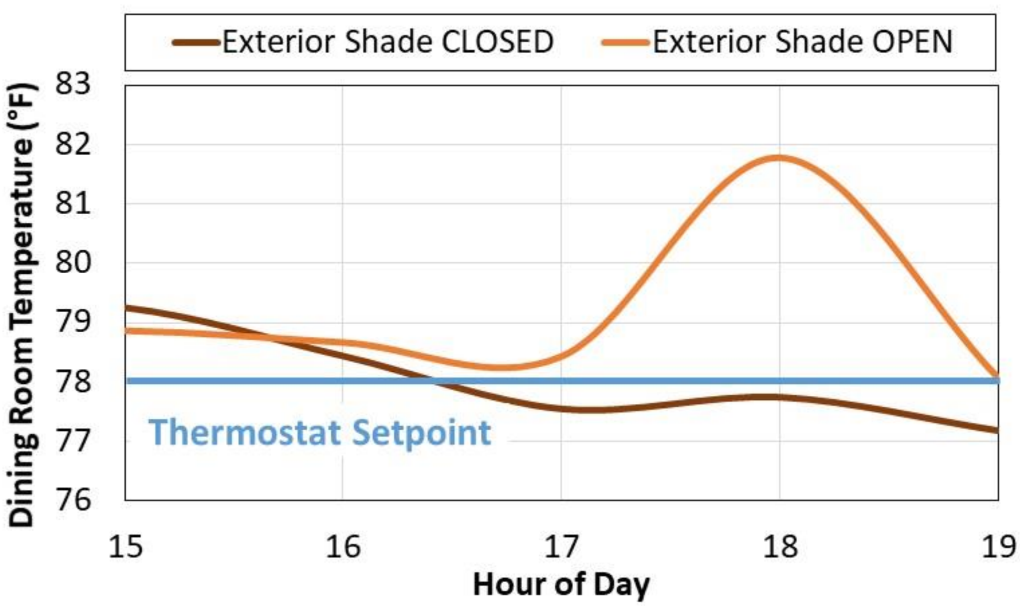


Figure 27. Indoor Temperature Impact of Exterior Shade at Field Site 3

Field Site 3 had large trees in the backyard that provide afternoon shade to the home, the westside of the home receives direct sunlight during the early evening hours. In addition, the exterior shade for Field Site 3 covered an older patio door, which likely had lower-performance characteristics (relative to the other field sites) and are similar to the patio doors of the PNNL Lab Homes (see Table 1). The combination of this lower-performance window and pronounced solar gains is reflected in the temperature profile shown in Figure 27.

To fairly compare HVAC use between shaded and unshaded cases at the occupied field sites, the following criteria would generally be necessary for the two cases: similar outdoor temperature and solar irradiance, similar HVAC setpoint, and similar occupant behavior (i.e., internal home loads). One such comparison was identified for Field Site 1, when the home was unoccupied for consecutive days and the research team was able to adjust the exterior shades during that timeframe. On one identified day, the exterior shades were open for the 24-hour day, while the shades were closed on another 24-hour day with similar outdoor conditions. The home's thermostat was set identically on each of the two identified days. Table 9 provides a comparison of the two similar days with daily averages for outdoor temperature, outdoor solar irradiance, indoor temperature at the thermostat, and the outdoor HVAC unit's current. With the home's exterior shades closed and offering shade to the home's dining room and bedroom, the outdoor HVAC unit's average current was approximately 1.0 amps less. This would translate to an approximate energy savings of 4 to 5 kWh, which corresponds to the higher end of the kilowatt-hour savings resulting from Lab Homes experiments (see Section 3.2.2 of this report).

Table 9. Exterior Shades Impact on HVAC Use at Field Site 1

Daily Averages of Key Metrics	Exterior Shades Open for 24-hr Day with Home Unoccupied	Exterior Shades Closed for 24-hr Day with Home Unoccupied
Outdoor Temp (°F)	84.3	84.4
Solar Irradiance (W/m^2)	262.8	25°.6
Indoor Temp at Thermostat (°F)	74.6	74.6
Outdoor HVAC Unit's Current (Amps)	5.8	4.8

5.0 Conclusion

This study evaluated exterior shades at the PNNL Lab Homes and three occupied field sites in Richland, Washington. The side-by-side PNNL Lab Homes were primarily used to examine the impact of the use of exterior shades on air-conditioning energy consumption. Exterior shades were installed on the large west-facing and south-facing windows of the Experimental Lab Home. When compared to interior vinyl blinds, exterior shades demonstrated daily HVAC energy savings from 1.0 to 3.2 kWh, as a function of the outdoor conditions. For the PNNL Lab Homes, these energy savings equate to an approximate 10% savings for air-conditioning when including internal loads. When compared to the Lab Home that had no shading on the same west- and south-facing windows, the application of exterior shades yielded an average HVAC savings of 20% when including internal loads.

At the occupied field sites, the exterior shades were consistently used by homeowners to reduce glare and improve comfort in the associated indoor space. Closing the exterior shades during peak solar irradiance hours resulted in indoor temperature reductions from 0.5°F to 4.0°F, offering improved comfort at the field sites. Consensus across the three homeowners indicated that the ability to see outside with the shades closed was a desirable feature of the shading technology. Exterior shades may offer an effective shading option for U.S. homes that have large west-facing or south-facing windows.

6.0 References

Cort KA, JA McIntosh, GP Sullivan, TA Ashley, CE Metzger, and N Fernandez. 2018. *Testing the Performance and Dynamic Control of Energy-Efficient Cellular Shades in the PNNL Lab Homes*. PNNL-27663, Pacific Northwest National Laboratory, Richland, Washington. Available online at https://www.osti.gov/servlets/purl/1477792

Knox JR and SH Widder. 2014. *Evaluation of Low-e Storm Windows in the PNNL Lab Homes. PNNL23355, May 2014.* Pacific Northwest National Laboratory, Richland, Washington. Available online at: http://labhomes.pnnl.gov/documents/PNNL_23355_Lab_Homes_Low-e_Storms.pdf.

Petersen JM, Sullivan GP, and Cort KA. 2016. *Evaluation of Cellular Shades in the PNNL Lab Homes.* PNNL-24857, Rev 2, Pacific Northwest National Laboratory, Richland, Washington. Available online at http://labhomes.pnnl.gov/documents/PNNL_24857_Cellular_Shades.pdf.

Petersen JM, Sullivan GP, Cort KA, MB Merzouk, V Srivastava, and JM Weber. 2015. *Evaluation of Interior Low-E Storm Windows in the PNNL Lab Homes.* PNNL-24827, Pacific Northwest National Laboratory, Richland, Washington. Available online at https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-24827.pdf

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