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Evaluation of Interior Cellular Shades in a Residential Building

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OAK RIDGE NATIONAL LABORATORY
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Buildings and Transportation Science Division

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EXECUTIVE SUMMARY

Windows are major contributors to energy demand in residential homes because of their inferior thermal resistance compared with the opaque envelope and sometimes from unwanted solar heat gain. Window attachments can help to mitigate this demand by controlling the solar heat gains and enhancing the thermal resistance of the windows. In this study, the energy savings potential of cellular shades in residential homes is studied using experimental testing and energy simulations. The energy performance of the shading devices was experimentally tested during the heating season from December 2019 to May 2020 with a focus on cellular shades. Five shading devices—three single and two double cellular/cell-in-cell shades—were used to compare the performance with generic horizontal (venetian) blinds using two nearly identical side-by-side rooms in a residential building with their exterior window facing east. Another objective of the experimental testing was to evaluate any impact of the side-channel of the shading device on energy savings. To observe the impact of the side-channels on energy savings, from shades in two of the test cases, cellular shades with side-channels were used. From the experimental testing, daily energy savings in the range of 9% to 23% were observed by considering data from 6 p.m. until 6 a.m. of the next day.

An energy model was created following the experimental testing for the baseline case to evaluate if the shade model, when added to the baseline, represents the reality of the cellular shades' performance. The model developed showed good agreement with the experimental data to represent reality for the energy impact of the cellular shades. The residential prototype buildings were then used for the energy simulation of different shades that were used during the experimental testing. The buildings used were single family buildings with conditioned floor area of 2377 ft^2. The energy simulations were performed for 15 locations/climate zones, and the impact of shades on varying climate conditions was evaluated for potential energy savings compared with the case without any shading device. The results showed that the energy savings up to 3 $kBtu/ft^2$-yr can be achieved in cold climates. Even in hotter climate zones (for example, ASHRAE climate zones 2A and 3A), overall energy savings were achieved from the use of cellular shades and the simple strategy designed to control the shades for application in the heating season. In relative terms, the total site energy savings for heating and cooling was up to 9% for the house with heat pump and up to 15% for house with gas furnace from cellular shades compared to the case without any shading device.

Overall, the results from the experiments and energy simulations showed that cellular shades provided higher thermal resistance and thus higher heating energy savings compared with conventional venetian blinds. The results also showed that the use of side-channels can help to improve the energy benefits of the shading system in residential buildings. Because the control of shades in this study focused on the heating season, the strategy used resulted in some penalties during the cooling season. This suggests that weather/climate-appropriate control of cellular shades could achieve higher energy savings compared with the simple control of the shade without any variation across seasons and climate zones used in this study.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

Windows cause significant energy demand in residential buildings because of their high thermal transmittance (compared with the opaque envelope) and their transmission of solar heat gain. Window attachments represent a cost-effective opportunity to save energy in new and existing buildings. Improved thermal performance of window attachments will increase the energy savings potential of these products. These products have the economic potential to save nearly 800 TBtu of energy by 2030 [1]. In residential buildings, shading devices are primarily used for maintaining privacy but can also provide energy savings by controlling solar heat gain or thermal transmittance. Interior shading devices are popular in residential homes because of their ease of maintenance, smooth operation, and aesthetic appeal.

Different types of shading devices are used in US households; blinds account for more than 60% and curtains approximately 19% of the all window coverings in US homes [2]. Although blinds might be able to reflect or block certain amount of solar radiation when needed, they do not provide significant improvement on window system thermal transmittance [3]. Simulations have shown that cellular shade can achieve higher energy savings than other types of shading devices [4]. For empirical validation of such claims from simulations, extensive testing of shades should be performed using different control strategies and on different locations with varying climates.

This study focuses on cellular shades, which have superior thermal insulation properties compared with other shading devices, such as generic horizonal (venetian) blinds, that are generally used in the homes. This study will quantify the energy savings potential of cellular shades using experiments and energy simulations. The experiment tests were performed with the objective of evaluating the performance of different types of cellular shade and the side-channels that are used, along with the shading device that can prevent air circulation between the window-shade gap and the interior of the rooms where the shades are installed. The shading devices used in this study cannot be modeled using energy simulation software such as EnergyPlus because of their complex structure [5]. Therefore, complex fenestration system properties of the shading devices were calculated using WINDOW [6] before using those systems in the energy simulations. The shading devices thus modeled were then used for energy simulations to assess their annual performance in varying climate conditions and varying constructions of typical prototype buildings in those locations.

2. EXPERIMENTAL TESTING

The first objective of this study was to carry out experimental testing of different types of shading devices to evaluate their energy savings potential during the heating climate. Several types of cellular shades were used, which are discussed later in this section along with the test setup, data collection, and the results from the experimental testing.

2.1 BACKGROUND

Before developing this plan for the experimental testing, some previous experimental testing was conducted from March to May 2019 using different configurations for a single type of cellular shade, which is briefly discussed in Appendix A1. Since, the previous testing used a single room, coinciding evaluation of cellular shade performance was not possible. The experimental setup discussed in this study followed to evaluate the impact of different types of cellular shades, as well as side-channels for the shades in the residential building, compared with generic venetian blinds.

2.2 EXPERIMENTAL SETUP

The experimental testing was performed in the Yarnell Station house of Oak Ridge National Laboratory in Knoxville, Tennessee, which lies in ASHRAE climate zone 4A and has Heating Degree Days/Cooling Degree Days of 3594/1514 with a base temperature of 65°F. Yarnell Station is a two-story single family detached house built in 2009. The house has slab foundation with above grade wall with R-13 insulation and R-38 blown-in attic insulation. The house is equipped with 80 AFUE heating system and 13 SEER cooling system for the conditioning. The whole house infiltration rate from the blower door test was 2476 CFM at 50 Pa. The experimental testing was performed from December 2019 to May 2020. Some preliminary testing, including test setup, normalization testing, and baseline test room calibration, was performed in November and December 2019.

2.2.1 Room Geometry

Two approximately identical east-facing rooms in the residential building shown in Figure 1 were used for the experimental testing. These test rooms were selected so that parallel comparison could be made between two test rooms with different types/controls of shades. The rooms have identical windows of 29.2 ft^2 (70"× 60.25") with a U-factor of 0.35 $Btu/h{\cdot}ft^2{\cdot}F$ and solar heat gain coefficient (SHGC of 0.26. The test room on the south side will be referred to as “Room A” and on the north side will be referred to as “Room B.” The test rooms and their floor plans are highlighted in Figure 1.

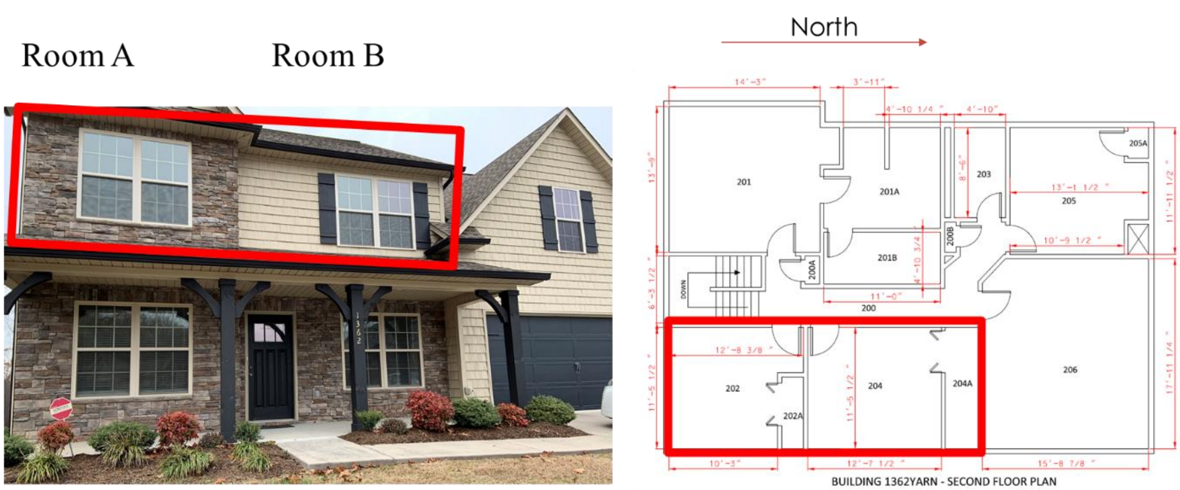

Figure 1. Rooms used for experimental testing and their floor plans.

2.2.2 Heating Equipment

Instead of using supply air from heat pump for conditioning of the test rooms, the plenums of both test rooms were sealed, and the heating was provided with electric room heaters. One of the reasons for doing this is there was no room-level monitoring of supply air temperature or flow rate in the house, which did not allow the calculation of the heating load in each of the rooms separately. Even with the availability of data such as supply air temperature or flow rate, the degree of uncertainty of load calculation using an air system is higher compared with an electric room heater. Therefore, to mitigate such uncertainty from the heating system, two identical electric room heaters, which provided convective heating, were used in both test rooms.

2.2.3 Sensors

Different sensors were used for monitoring various variables such as temperature, relative humidity, and solar irradiation, which can be used to analyze the impact of shading devices on different variables and to diagnose any potential issues that might occur during testing. Details of the sensors used during the experimental testing is provided in **Error! Reference source not found.**. A photograph taken showing the cellular shades and a few sensors installed in Room B is shown in Figure 2.

Table 1. Sensors used during experimental testing.

S.	Measurement	Device	Quantity
1	Room heater power /energy	CCS Advanced Wattnode	2
2	Ambient temperature	Thermistor, 192-103LET	1
3	Transmitted vertical solar irradiation (inside)	Pyranometer, Eppley PSP	2
4	External vertical irradiation (east side)	Pyranometer, CS320	1
5	Room air temperature	Thermistor, 192-103LET	4
6	Window surface temperature (inside)	Thermistor, 192-103LET	12
7	Window surface temperature (outside)	Thermistor, 192-103LET	2
8	Gap air temperature (gap between window and shading)	Thermistor, 192-103LET	4
10	Relative humidity (room)	Honeywell HIH-4000	2
11	Mean radiant temperature	Global thermistor, 192-103LET	2

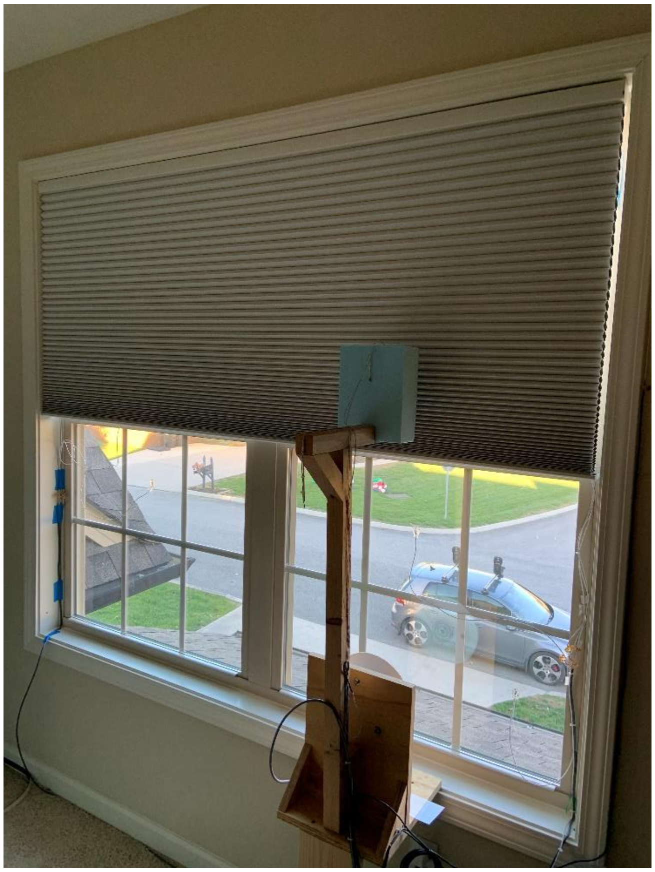

Figure 2. Photo of sensor installation and one of the cellular shades (in the half open position) in Room B.

2.2.4 Shade Selection and Test Cases

Different shading devices and settings were used for experimental testing. The shading devices used along with their properties are listed in Table 2 and the properties of glazing system with window at Yarnell house window and shade is provided in Table 3. Further, the properties of glazing system with Attachment Energy Rating Council (AERC) and shades used in this study is provided in Appendix A2. Six types of shading devices, including venetian blinds, were used for testing. For all the test cases, venetian blinds were used as a baseline case, assuming a typical home/room has venetian blinds as the shading device installed in its windows.

Table 2. Shade properties (standalone).

Shade	Type	Thickness (in.)	(T_{sol})	(R_{sol})	T_{vis}	R_{vis}	O	ε	T_{IR}
C22	Cell-in-cell cellular (light-filtering)	1.25	0.060	0.583	0.059	0.624	0.009	0.988	0.000
C23	Cell-in-cell cellular (room-darkening, low-e)	1.25	0.000	0.686	0.000	0.719	0.000	0.985	0.000
E40	Single cell (light-filtering)	1.25	0.263	0.577	0.262	0.622	0.107	0.977	0.017
E41	Single cell (room-darkening; low-e)	1.25	0.000	0.672	0.000	0.693	0.000	0.851	0.000
SS	Single cell (room darkening)	1.25	0.000	0.633	0.000	0.809	0.000	0.866	0.000
VB	Aluminum venetian blinds	1.00	0.000	0.5	0.000	0.551	0.000	0.820	0.000

T= transmittance, R=reflectance, sol=solar, vis=visible, O=openness, E=emissivity, IR= infrared

Table 3. Shade properties mounted on the Yarnell house window.

Shade	U-factor (Btu/h·ft^2·F)	SHGC	T_{vis}
None	0.294	0.296	0.553
C22	0.185	0.134	0.039
C23	0.163	0.103	0.000
E40	0.211	0.154	0.172
E41	0.166	0.110	0.000
SS	0.192	0.094	0.000
VB	0.249	0.193	0.024

The different test cases were defined based on the different type of shading device installed in the two test rooms. In the case of the VB, the blinds were left in the same position throughout the day. In the case of the other shades, the shades were closed from 6 pm to 6 am and open at other hours. This assumption for closing and opening of the shade was made for two reasons: the first is that the residents in a home would likely lower their shades in night hours for privacy reasons, and the second is because we were interested in heating energy savings potential of the shading device. In the case of the VB, the blinds were left in the same position throughout the day, assuming a typical scenario in which the user would leave the blinds in the same position without any automation to operate the blinds. All the different cases for which the experimental testing was performed with respective shade installed in Room B and the number of days for which the testing was performed for each case is provided in Table 4. In Room A, VB were the only type used for all the test cases listed in Table 4. In the table, two of the cases, 3 and 6, had shade with side-channels. Side channels which were added to eliminate any light from entering the room also helped limit the circulation of the air in the gap between the window and the cellular shade with the test rooms.

Table 4. Different testing performed with respective shade in the two rooms and the number of test days for each case.

Test case	Cellular shades in Room B	Number of test days
Baseline	—	6
Case 1	E41	8
Case 2	SS	8
Case 3	C23-SC	11
Case 4	E40	12
Case 5	C23	13
Case 6	SS-SC	10
Case 7	C22	14

Note: SC = side-channels

2.2.5 Normalization and Baseline Testing

The two test rooms had different energy consumptions between them and to resolve this issue, several steps were taken before beginning testing. This testing was performed without any blinds in the test rooms. The room temperatures of both rooms were controlled within 1°F dead band. The difference between the heating energy consumption of the test rooms during late November and early December is shown in Figure 3. The difference in the daily energy consumption of the Room B from Room A was around 20% to 35% of the energy consumption by Room A.

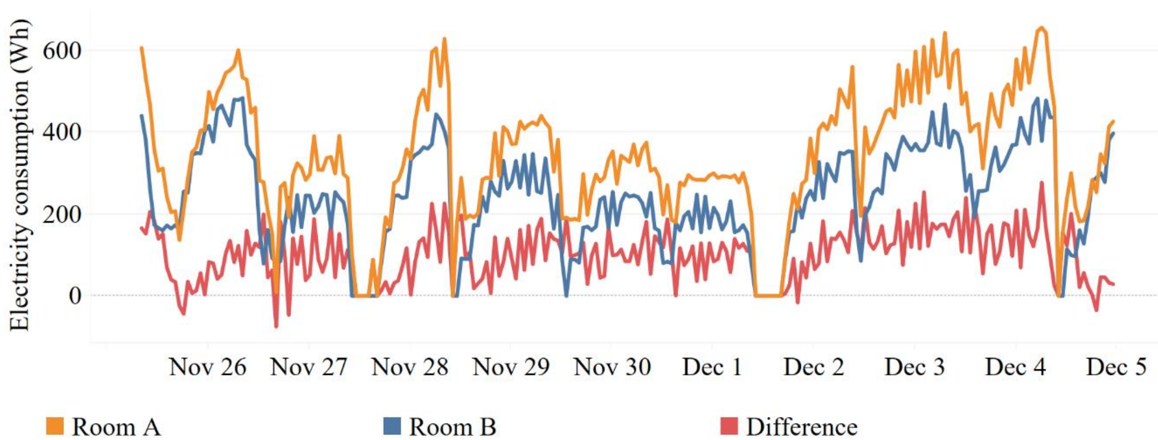

Figure 3. Test room heater energy consumption and its difference (Room A - Room B) before using any insulation in Room A.

To address these discrepancies, insulation was added to Room A as the south wall faced the outdoors. We added a vacuum insulation panel (VIP) with R-35 thermal resistance to significantly reduce the heat transfer through that wall. We also performed a blower door test to ensure that discrepancies were not due to different air leakages in the rooms. For example, Figure 4 shows the surface temperature of one of the wall corners in Room A before and after installing the VIP. In the figure, the temperature variation was reduced from 12.6°F (7°C) to 7.2°F (4°C) after the installation of the VIP. Figure 5 shows the setup for the blower door test that was performed in the test rooms. The results from the blower door test showed an air flow rate of 109 CFM in Room A and 125 CFM in Room B at 50 Pa, which shows that there is no significant difference in the infiltration rate of the test rooms. The existing air-conditioning vents on the test rooms were also sealed to prevent any air leakage between the test room and existing air-conditioning system of the home, which was not used for the purpose of this testing. Then, new heaters were installed in the test rooms, replacing the old ones to reduce any discrepancy in the electricity consumption from faulty heater/readings.

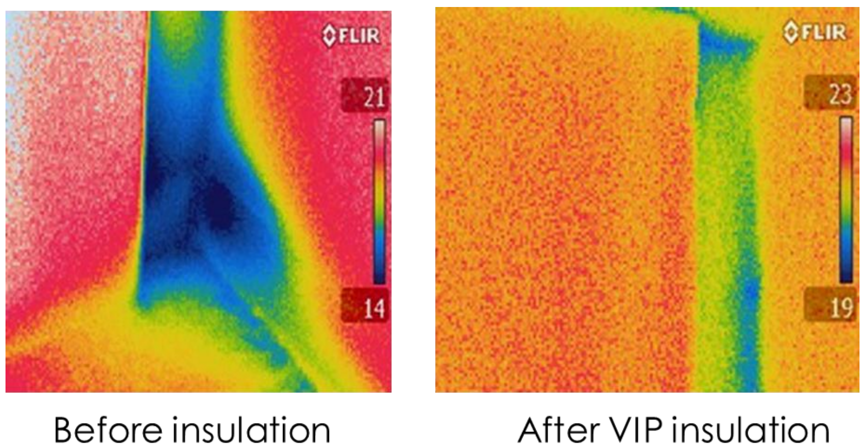

Figure 4. The surface temperature (in Celsius) of one of the south wall corners in Room A before and after insulation.

Figure 5. Blower door test setup in Room B.

Then, VB was installed in Room A which is our baseline case and also helped to reduce the difference in energy consumption between the two test rooms. We found that the VB being closed and blocking the solar radiation during the day hours (6 a.m. to 6 p.m.) created a higher difference between the heating energy demand from the test rooms. The transmitted solar radiation in the test rooms and the external vertical irradiation for one week of January 2020 in the east orientation is shown in Figure 6, which shows that higher solar radiation is transmitted to Room B, where the window does not have any shade from 6 a.m. to 6 p.m.

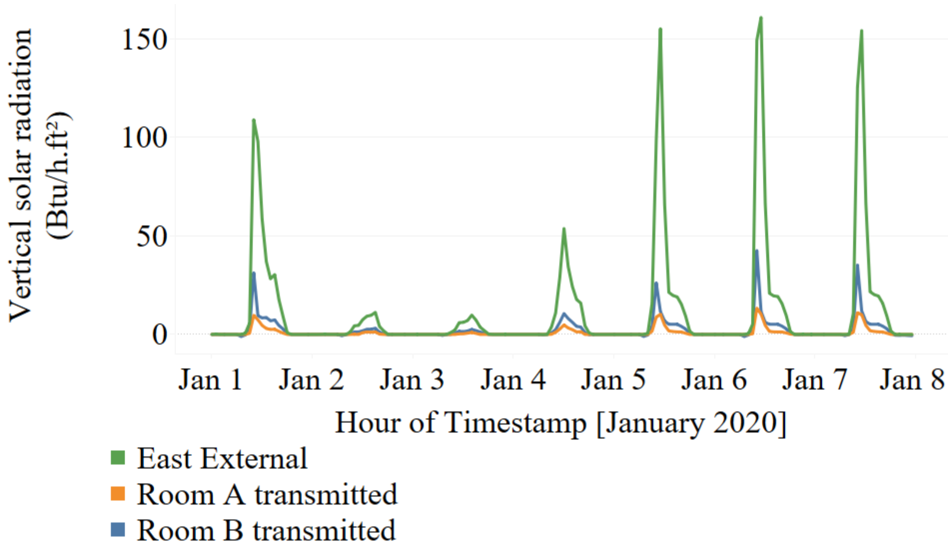

Figure 6. External and transmitted vertical solar irradiation in the east orientation.

To reduce this impact of solar irradiation, we only used data from before 6 a.m. and after 6 p.m. for our analysis of the experimental data, which will be referred as "night hours" hereafter. The electricity used by the heater after using these different measures with the VB in Room A and no shading device in Room B is shown in Figure 7. Here, the overall percentage difference in energy consumption of two rooms was within 1%.

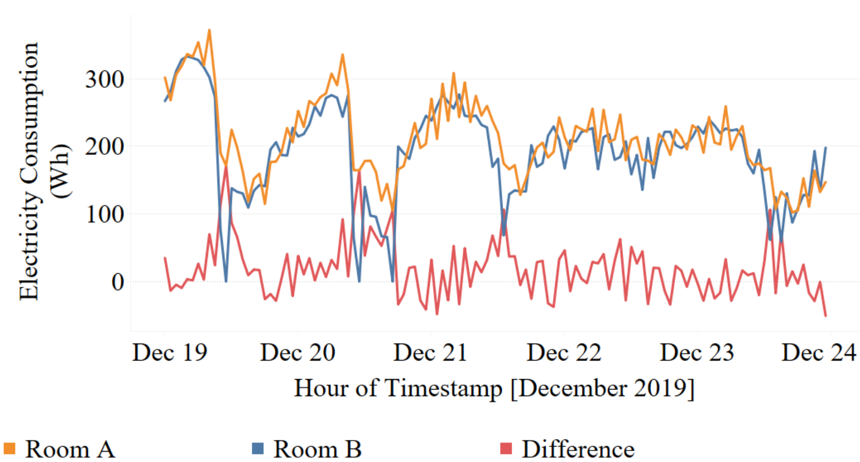

Figure 7. Test room heater energy consumptions and their difference after using the VIP and VB in Room A.

2.3 RESULTS

The results from the experimental testing are presented in the form of the difference of heater electricity consumed at the test rooms to maintain a temperature setpoint of 72°F in each room. Table 5 provides the average daily heating energy/electricity consumption data and absolute and relative savings from the use of cellular shades in Room B against VB in Room A, collecting the data during the night hours. Here, the energy savings are the difference of energy consumption by Room B vs. Room A, which is the baseline test room; percentage savings are the energy savings as a percentage of Room A's energy consumption. In Table 5, from the use of a shading device, the energy savings are in the range of 9% to 23%, which was −0.3% when no shading device was used in Room B for the baseline testing. For the baseline case, the daily average energy consumption was 2,644 Wh in Room B and 2,636 Wh in Room A. When considering the data for 24 h, the energy savings were in the range of 12% to 24%, whereas the difference from Room A to Room B without any shade was 9%. Table 5 shows that in general, the energy savings were higher for cell-in-cell shades C22 and C23 compared with single-cell E40 and E41. In the case of the SS, the energy savings were very low when no side-channel was used compared with the SS-SC, which showed energy savings of 22%. However, since the weather during the period of different cases was not the same, a direct comparison between the different shading devices cannot be made. To make a direct comparison, more experimental testing with side-by-side comparisons of shading devices of interest would be required. Also, the measured energy consumption and savings results depend on weather conditions during testing. Therefore, because of different weather conditions, the results from annual simulations might be different from the experiments performed for a period of 6 to 14 days.

Table 5. Average daily energy consumption and savings in the test rooms (data collected from 6 p.m. to 6 a.m. the next day).

Test case	Room B shade	Daily energy consumption of room with cellular shades: Room B (Wh)	Daily energy consumption of room with VB: Room A (Wh)	Savings (Wh)	Savings (%)
Case 1	E41 (low-e)	1,389	1,529	140	9.1
Case 2	SS	1,031	1,164	133	11.4
Case 3	C23-SC (low-e)	2,309	2,933	625	21.3
Case 4	E40	1,354	1,552	197	12.7
Case 5	C23 (low-e)	1,775	2,173	399	18.3
Case 6	SS-SC	1,415	1,817	402	22.1
Case 7	C22	1,003	1,257	255	20.2

The temperature of the test rooms during testing was maintained by electric heaters and sometimes free floated during high ambient temperature since no cooling was performed. The temperature for a few days of testing in Feb 2020 is shown in Figure 8. The figure shows that from morning hours around 9 a.m. until afternoon hours around 2 p.m., the temperature in Room B was higher than in Room A since Room B did not have any shade deployed during that time and allowed solar radiation to enter the room. Room A, which has VB, blocked the useful solar radiation and thus might require some heating energy that was not needed in Room B, which was why the data from 6 p.m. to 6 a.m. was taken for energy savings evaluation. The figure also shows that during other time periods, the temperature of the test rooms was quite similar to each other and was well maintained from the use of the electric heater around the set-point temperature of 72°F.

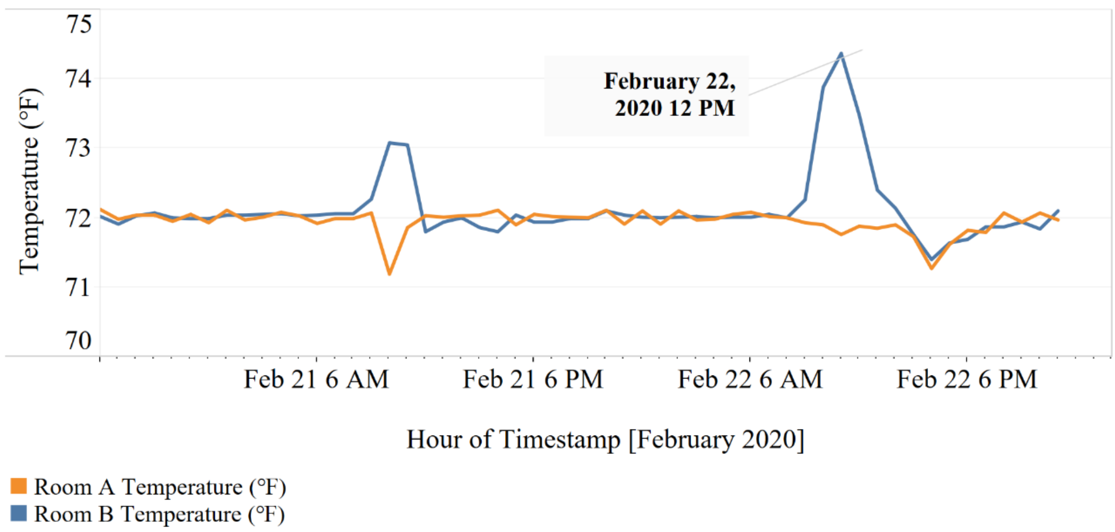

Figure 8. Temperature in Room A and Room B during a period of experimental testing.

3. MODEL CREATION AND COMPARISON

An energy model was created for the house where the experimental testing was carried out. The objective of the model was to simulate the heater energy consumption and compare it with the measured data and check if the model for the cellular shades made reasonable predictions for energy consumption of the test rooms.

3.1 ENERGY MODEL FOR YARNELL STATION

The energy model for the house where the experimental testing was performed was created using the Sketch-up OpenStudio plugin and then modified in EnergyPlus [5]. The geometry and the material properties of the house were assigned following the construction document/information available on the Yarnell Station house. The weather file was created based on temperature collected at the Yarnell house and solar radiation from a nearby location. The two rooms used for experimental testing were used for the simulation to check the performance of simulation model for different shade attachments versus the experimental data. The geometry of the model of the test rooms is as shown in Figure 9 with the floor height of 8 ft.

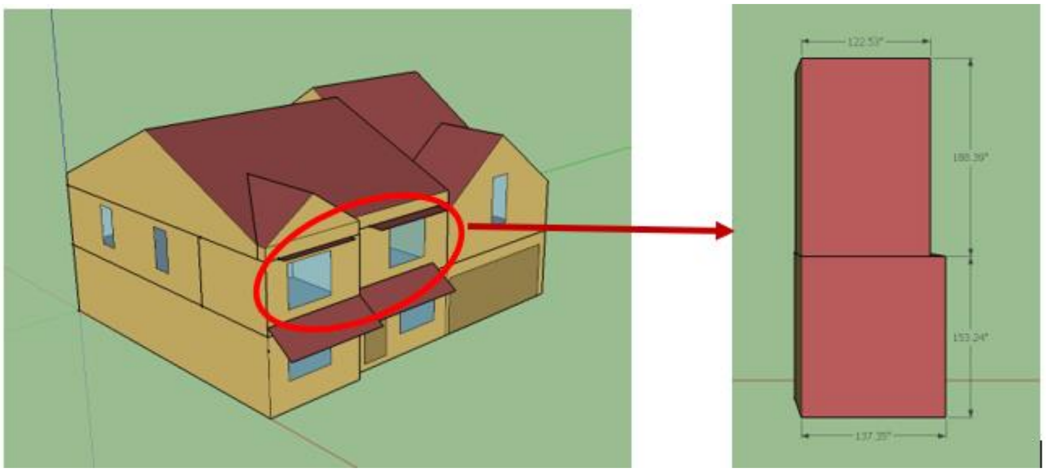

Figure 9. Energy model geometry and the size of the test rooms.

3.1.1 Model Details

The construction of different parts of the building is provided in Table 6, which lists the different layers of material for construction of the roof, wall, ceiling, and floor from the outside layer to the inside layer as defined in the EnergyPlus model. In the case of Room A, a layer of insulation was added in the south wall to represent the VIP added for insulation in the experiment, which is shown as Layer 6 for “External wall,” which is not present for other external walls. For the boundary conditions, the boundary was defined as the ground for the floor of the first floor and outdoors for the exterior envelope. Between the interior wall and the ceiling, the surface of the adjacent zone was used as the outside boundary.

Table 6. Construction of the Yarnell house model.

Construction	Roof	External wall	Internal wall	Internal ceiling	Attic floor
Outside layer	Asphalt shingle	Exterior insulation and finish system (EIFS)	Gypsum board 5/8 in.	Carpet w/ fibrous pad	Gypsum board 5/8 in. ceiling
Layer 2	30# felt	Huber ZIP ½ in.	ZEHcor wall	Hardboard flooring	Cellulose insulation 15 in.
Layer 3	Tech shield roof deck 7/16 in.	Exterior Wall Cavity	Gypsum board 5/8 in.	Advantec deck ¾ in.	
Layer 4	Expanded Polystyrene (EPS) foil faced	Gypsum board ¼ in. foil faced		Truss gap	
Layer 5		Gypsum board ¼ in. paint		Gypsum board 5/8 in. ceiling	
Layer 6		Insulation (Room A- south wall)			

3.2 COMPARISON WITH THE MEASURED DATA

First, the model was compared with the measured data in terms of heating energy/electricity consumption for the baseline case to make any necessary adjustments to the model to calibrate it with the experimental data. The model showed very good alignment with the measured data and thus, further calibration of the model was not needed in this case. Figure 10 (a) shows a comparison of the measured and simulation data for the baseline case for Room A and Room B. Figure 10 (b) provides the graph for weather variables during the baseline testing period.

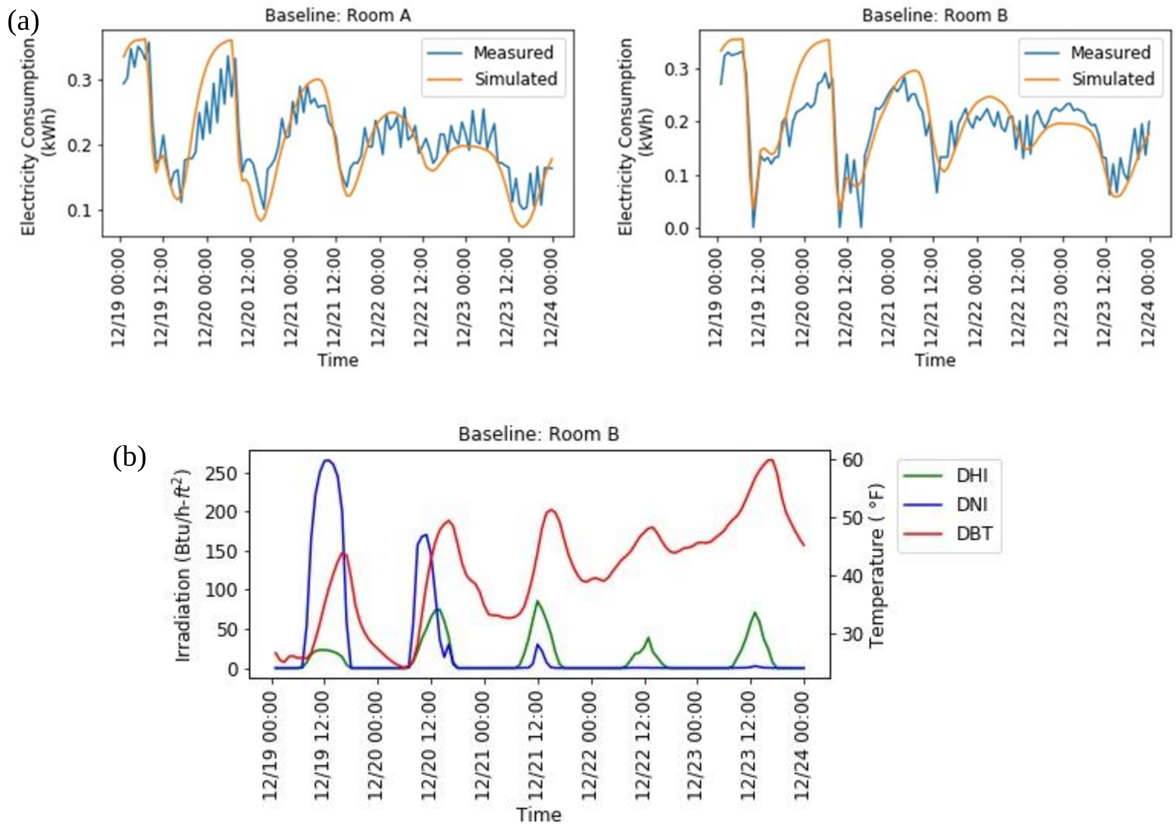

Figure 10. (a) Measured and simulated heater electricity consumption for Room A and Room B; (b) weather data for the baseline comparison period: diffuse horizontal irradiation (DHI), direct normal irradiation (DNI), and dry bulb temperature (DBT).

Detailed models of the shades used in each of the cases were prepared using WINDOW 7 and THERM. These models were then exported into EnergyPlus. Furthermore, the hourly simulation data was compared with the measured data using mean biased error (MBE) and coefficient of variation of root mean squared error (CV-RMSE) for the different cases of experimental testing and their corresponding energy simulation for a period of approximately one month. The recommended value for MBE is within ±10%, and for CV-RMSE is below 30% for the hourly data according to ASHRAE guideline 14 [7]. The results for the measured and simulated energy consumption, MBE, and CV-RMSE individually for both rooms are provided in Table 7.

Table 7. Comparison of measured and simulated heating energy consumption for different test cases for Room A and Room B.

Room	Case	Measured (kWh)	Simulated (kWh)	MBE	CV-RMSE
Room B	Baseline	22.9	23.7	−3.7	22.7
Room A	Baseline	25.1	24.7	1.7	18.0
Room B	Case 1	16.4	17.2	−5.1	36.5
Room A	Case 1	19.3	18.8	2.9	25.3
Room B	Case 2	12.2	15.5	−26.8	60.1
Room A	Case 2	14.5	16.7	−15.1	42.3
Room B	Case 3	47.8	55.9	−17.0	30.4
Room A	Case 3	57.9	61.6	−6.4	16.6

Based on the MBE and CV-RMSE shown in Table 7, we concluded that the simulated models of all the shading systems for all the cases are reasonable. The figures for the comparison of measured and simulated data for the test cases is provided in Appendix A3. The objective of the calibration was to determine the confidence in the performance of cellular shade models. These models were then used in the whole-building energy simulation models for generalizing the energy performance of these shading systems for different building types and climate zones.

4. SCALE-UP OF ENERGY SIMULATION

4.1 SIMULATION METHODOLOGY

The energy simulation was performed for the various shades used during the experimental testing for 15 locations using single-family 2018 IECC residential prototype buildings [8], which have a conditioned area of approximately 2,350 ft^2. The respective TMY3 files for the different locations were used as weather data for the simulation. To generalize the impact of foundation and air conditioning system types, the following set of prototype buildings was used for the energy simulation.

Foundation: (1) Slab (2) Unheated basement
Heating system: (1) Gas furnace (2) Heat pump

The geometry of the prototype buildings with two different types of foundation is shown in Figure 11.

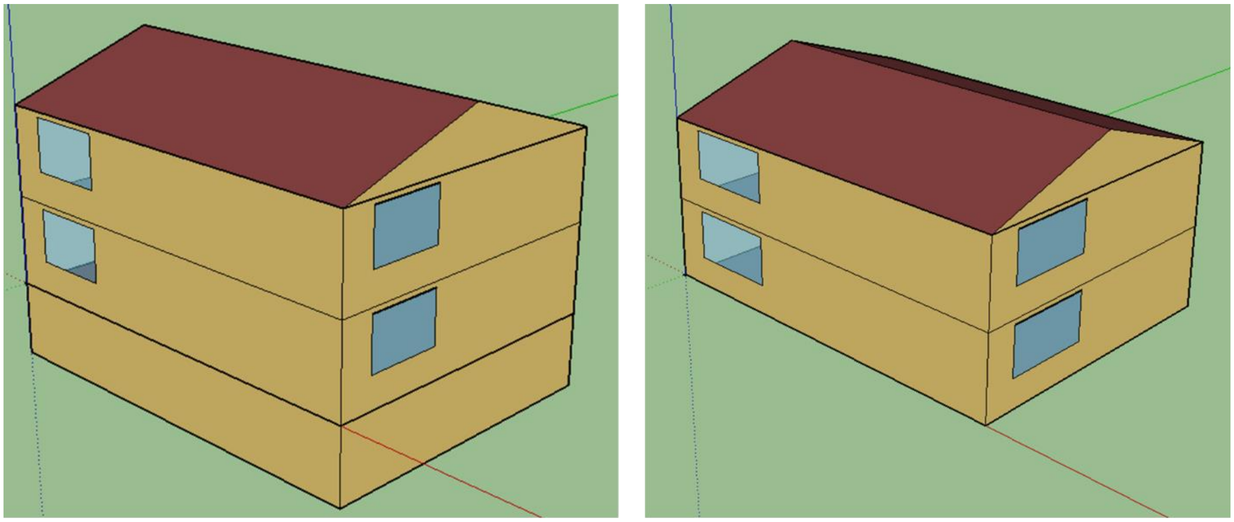

Figure 11. Geometry of the prototype buildings with different foundation types: (left) with an unheated basement and (right) with a slab.

Different climate zones and locations for which the energy simulation was performed are listed in Table 8. In the table, the properties of the window that was used for these different locations are also provided to replace the simple model of the window with a complex fenestration representation of the window as a baseline case for the complex fenestration system of the glazing and shading system. Four different windows were used across the 15 climate zones, and those windows were assigned such that the SHGC and U-factor of the window was similar to the simple window, which is described only using SHGC and U-factor in EnergyPlus.

Table 8. Different climate zone and window properties used for residential prototype simulations.

Climate	Location	Window	
		U-value (Btu/h·ft^2·F)	SHGC
1A	Miami	0.378	0.238
2A	Houston	0.378	0.238
2B	Phoenix	0.378	0.238
3A	Memphis	0.322	0.221
3B	El Paso	0.322	0.221
3C	San Francisco	0.322	0.221
4A	Baltimore	0.323	0.309
4B	Albuquerque	0.323	0.309
4C	Salem	0.301	0.309
5A	Chicago	0.301	0.309
5B	Boise	0.301	0.309
6A	Burlington	0.301	0.309
6B	Helena	0.301	0.309
7	Duluth	0.301	0.309
8	Fairbanks	0.301	0.309

For each combination of location, heating system, and foundation, the different shades that were simulated were C22, C23, C23-SC, E40, E41, SS, SS-SC, and VB, which were the shades used for the experimental testing and described in Table 2, and a case without any shade as the baseline case. In the annual simulation, unlike in the experimental testing, the VB were also controlled in the same manner as other shades, closed at 6 pm and opened at 6 am throughout the year. Before running simulations for different test cases, a separate energy simulation was used as auto-size the run for each combination of 15 climate zones, 2 foundations, and 2 heating systems without using any shades in the building. This rated heating and cooling capacity, air flow rate, and sensible heat ratio of the system sized using these runs was used for energy simulations with shades. This was done so that only the shading device was the different parameter in the energy simulations, and all the heating/cooling system had the same parameters across different runs. Properties of the prototype buildings used for the simulation are provided in Appendix A4.

4.2 RESULTS

The results from the energy simulations are provided in detail for climate zone 4A, where the experimental testing was done, and a summary of results is provided for all the climate zones. For climate zone 4A, the results are provided for heating and cooling energy consumption and savings/loss per unit area as shown in Figure 12. The Energy Use Intensity (EUI) results are provided for both heating systems types; since there was not much variation across two foundation types, the results are only shown for the unheated basement. In Figure 12, the energy consumption for heating was much higher than for cooling in climate zone 4A, which was also true for energy savings, which were much higher for heating. The energy penalty for cooling demands was very low compared with heating energy savings for all types of shading devices. When comparing the gas furnace with the heat pump, the energy intensity was higher for the gas furnace because it had a burner efficiency of 0.8 and the heat pump had a rated coefficient of performance (COP) of 3.7. A similar trend was seen across the other climate zones, where the heating energy consumption and heating energy savings were higher while using the gas furnace. It is to be noted that the energy savings could vary depending on the construction of the house.

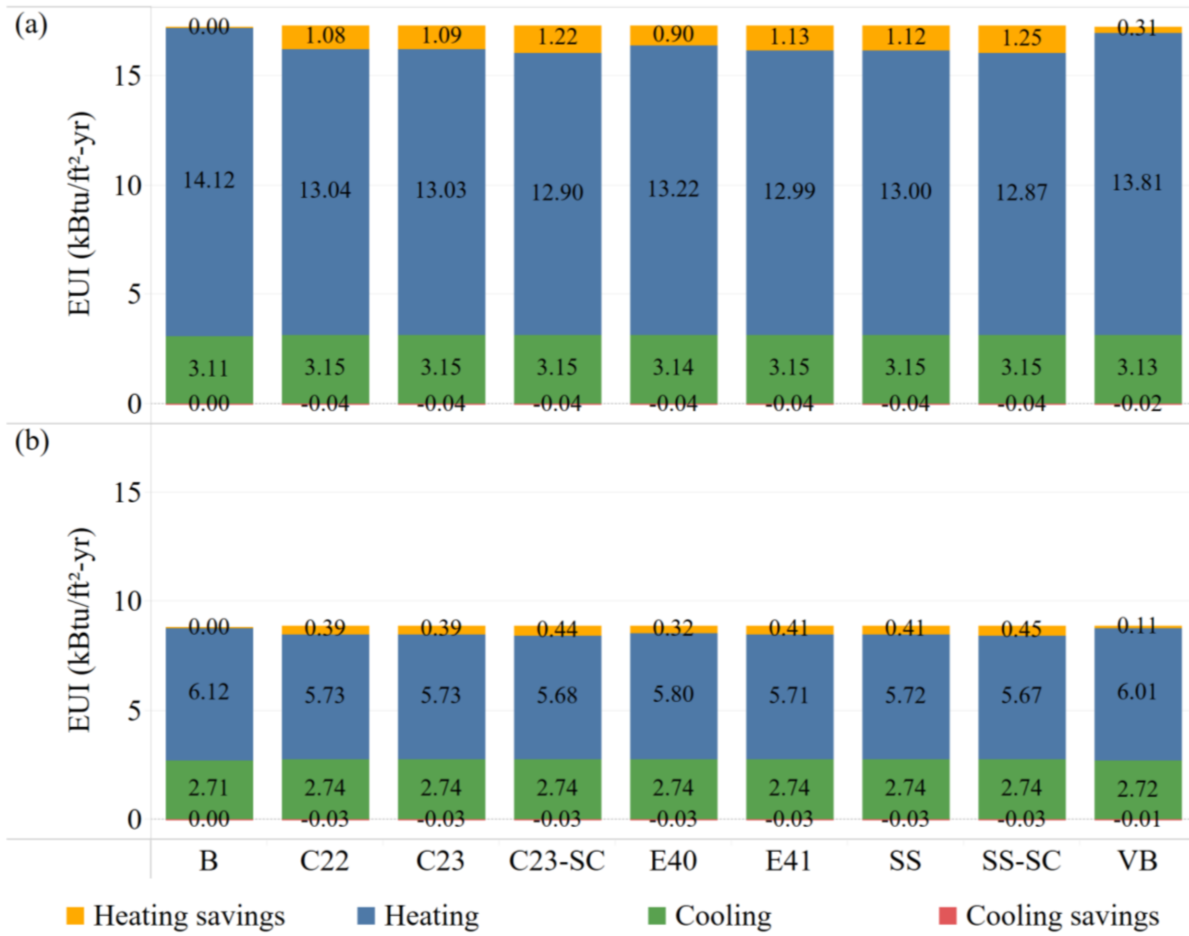

Figure 12. Energy consumption and savings for a house with an unheated basement in climate zone 4A with two different heating systems: (a) gas furnace and (b) heat pump. B = baseline

In Figure 12, the baseline case was used to calculate the heating and cooling savings for the case with other shading devices. The VB had the lowest energy savings of 0.31 kBtu/ft^2-yr among the shading devices, and the cases with side-channels (C23-SC and SS-SC) had the highest energy savings of 1.22 and 1.25 kBtu/ft^2-yr for the case with the gas furnace as the heating system. The corresponding electricity consumption of Figure 12 (kWh/ft^2-yr) is provided in Appendix A5.

The results for total energy savings for all the climate zones are provided in Figure 13. In the figure, the conditioned area normalized total energy savings from heating and cooling show that energy savings were achieved in all the climate zones except some cases in 1A. The energy savings were higher in the colder climates (i.e., from climate zone 1A toward climate zone 8). The figure shows that the energy savings from the use of cellular shades were up to 3 kBtu/ft^2-yr in climate zone 8 for the house with a gas furnace. In the case of the VB, the maximum energy savings were 0.5 kBtu/ft^2-yr compared with the case without any shade. The energy savings from the cellular shades were consistently 4–6 times the energy savings from the VB. While comparing the performance amongst cellular shades, E40 (which is a light-filtering cellular shade) saved less energy compared with other cellular shades. One cell-in-cell shade with side-channels (C23-SC) and another single-cell shade with side-channels (SS-SC) were able to achieve highest amount of total energy savings. The higher energy savings were present for the house with a gas furnace compared with a heat pump because of differences in their efficiency and thus energy consumption for heating. Figure 13 also shows that total energy savings did not vary much by the foundation type, although slightly higher energy savings were seen in the case of the slab compared with the unheated basement case. The energy consumption and savings in Figures 12 and 13 are provided in terms of site energy and the corresponding source energy is provided in Appendix A6. Since, the control strategies in our experiment, closed the shades from 6 pm to 6 am and opened during other hours, an additional control strategy with shade always closed was also run for different cellular shade across all the climate zones. The result for this additional simulation is provided in Appendix A7.

		Gas furnace								Heat pump							
		C22	C23	C23-SC	E40	E41	SS	SS-SC	VB	C22	C23	C23-SC	E40	E41	SS	SS-SC	VB
Slab	1A	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2A	0.7	0.7	0.7	0.5	0.7	0.7	0.8	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.0
	2B	0.6	0.6	0.6	0.5	0.6	0.6	0.6	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.0
	3A	0.8	0.8	0.9	0.7	0.9	0.8	0.9	0.2	0.2	0.2	0.3	0.2	0.3	0.3	0.3	0.0
	3B	0.7	0.7	0.8	0.6	0.7	0.7	0.8	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.0
	3C	1.0	1.0	1.1	0.8	1.0	1.0	1.1	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1
	4A	1.2	1.2	1.3	0.9	1.2	1.2	1.4	0.2	0.4	0.4	0.5	0.3	0.4	0.4	0.5	0.1
	4B	1.1	1.1	1.2	0.9	1.2	1.1	1.3	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.4	0.1
	4C	1.2	1.2	1.4	1.0	1.3	1.3	1.4	0.3	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0.1
	5A	1.5	1.5	1.7	1.2	1.6	1.6	1.8	0.3	0.7	0.7	0.8	0.5	0.7	0.7	0.8	0.1
	5B	1.3	1.4	1.5	1.1	1.4	1.4	1.6	0.3	0.5	0.5	0.5	0.4	0.5	0.5	0.6	0.1
	6A	1.7	1.7	1.9	1.3	1.7	1.7	1.9	0.3	0.9	0.9	1.0	0.7	0.9	0.9	1.0	0.2
	6B	1.7	1.8	1.9	1.4	1.8	1.8	2.0	0.4	0.8	0.8	0.9	0.7	0.9	0.9	0.9	0.2
	7	2.1	2.2	2.4	1.7	2.2	2.2	2.5	0.4	1.3	1.3	1.5	1.0	1.3	1.3	1.5	0.2
	8	2.5	2.5	2.9	1.9	2.6	2.6	3.0	0.4	1.7	1.8	2.0	1.3	1.8	1.8	2.1	0.3
Unheated basement	1A	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2A	0.6	0.6	0.7	0.5	0.6	0.6	0.7	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.2	0.0
	2B	0.5	0.5	0.6	0.4	0.5	0.5	0.6	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.0
	3A	0.7	0.7	0.8	0.6	0.7	0.7	0.8	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1
	3B	0.6	0.6	0.7	0.5	0.6	0.6	0.7	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.0
	3C	0.8	0.8	0.9	0.7	0.9	0.9	0.9	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1
	4A	1.0	1.1	1.2	0.9	1.1	1.1	1.2	0.3	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0.1
	4B	1.0	1.0	1.1	0.8	1.0	1.0	1.1	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.1
	4C	1.1	1.1	1.2	0.9	1.1	1.1	1.2	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.4	0.1
	5A	1.3	1.3	1.5	1.1	1.4	1.4	1.6	0.4	0.6	0.6	0.7	0.5	0.6	0.6	0.7	0.2
	5B	1.2	1.2	1.3	1.0	1.2	1.2	1.4	0.4	0.4	0.4	0.5	0.4	0.4	0.4	0.5	0.1
	6A	1.5	1.5	1.7	1.2	1.5	1.5	1.7	0.4	0.8	0.8	0.9	0.6	0.8	0.8	0.9	0.2
	6B	1.5	1.5	1.7	1.3	1.6	1.6	1.8	0.5	0.7	0.7	0.8	0.6	0.7	0.7	0.8	0.2
	7	1.9	1.9	2.1	1.5	2.0	2.0	2.2	0.5	1.1	1.1	1.3	0.9	1.2	1.2	1.3	0.3
	8	2.2	2.2	2.6	1.8	2.3	2.3	2.6	0.5	1.5	1.5	1.8	1.2	1.6	1.6	1.8	0.4

Total savings (kBtu/ft²-yr) 0.0 – 3.0

Figure 13. Total energy savings of different shading systems compared with the baseline case for all climate zones, foundation types, and heating systems.

The relative energy savings from the application of shade attachments is shown in Figure 14. This figure shows energy savings for the slab foundation and with a heat pump. Although the magnitude of percentage savings varied across different foundation and heating system types, the trend was similar across the shading system cases. In this case, the energy savings were in the range of 1.5% to 9% excluding climate zone 1A, where the savings were negligible. In the case of the residential prototype with a gas furnace, heating energy savings up to 20% and total (heating and cooling) energy savings up to 15% were observed. The results for percentage energy savings for all the different cases are provided in Appendix A8. In general, the relative (%) energy savings were higher in colder climate zones, but climate zone 3C (which is a relatively hotter climate zone) showed the highest amount of percentage savings. Climate zones 6A, 6B, and 7 showed a higher amount of relative energy savings compared with other climate zones. Climate zone 8, with the highest absolute energy savings, had relative energy savings around 5% from the use of cellular shades. The lower relative savings were due to higher heating energy consumption at this location. Use of the VB resulted in the savings of ~2% for all the climate zones.

Figure 14. Total relative heating and cooling energy savings for the shading systems in different climate zones for the case with a slab and a heat pump as the heating systems. (Note: the savings for different climate zones are represented by the combination of colors and shapes.)

5. CONCLUSIONS

The energy impact of the cellular shades was studied using both experimental testing and energy simulations. The results showed that the cellular shades have significant energy savings potential compared with conventional VB that are installed in the majority of the residential buildings at present. The VB were left in the closed position the entire time, whereas cellular shades were opened during the day and closed during the night with nighttime data selected for the analysis to avoid the influence of a difference in solar gain on the test rooms. Experimental testing showed that the use of cellular shades can achieve 9% to 23% energy savings during night hours compared with the case with the VB. From the results, we also observed that the shading devices with side-channels saved more energy compared with cellular shades without side-channels. This might require more investigation in the future under a more controlled environment to experimentally estimate the energy savings that can be achieved by using the side-channels and closing the gap between the shade and window jamb.

The energy simulations across different climate zones showed that total energy savings of up to 3 kBtu/ft^2-yr can be achieved from heating and cooling from the use of cellular shades in colder climates for the case with a heat pump as the heating system and slab as the foundation type. In terms of the percentage savings, the energy savings using cellular shades were up to 15% for total energy from heating and cooling and 20%

for only heating energy. Both absolute and relative energy savings varied with different types of heating systems, foundation types, and the locations of the building. In terms of site energy, absolute energy savings were higher for homes with a gas furnace compared with a heat pump, and homes with a slab achieved higher savings compared with homes with an unheated basement. The total percentage savings were lower compared with savings from experimental testing with data from 6 p.m. to 6 a.m. during the heating season, while the heating savings percentage was in a similar range. In general, when the use of cellular shades provided heating energy savings, it also resulted in a cooling energy penalty while controlled by closing the shades between 6 p.m. and 6 a.m. and opening them at other hours. This control strategy was used in this study because the experimental testing focused on the heating season and heating energy benefits that cellular shades can provide. Hence, to tap into the cooling energy savings potential, different control strategies used in this study should be explored in the future. In general, cell-in-cell shades and single-cell shades with low-e had similar thermal performance. In case of light filtering shades, cell-in-cell shade performed better than single-cell shades. Using simulations similar to the experimental testing, the side-channels enhanced the energy performance of the cellular shades.

The work done in this study showed that thermal performance of cellular shades was better compared with the VB, but to achieve higher savings, a comparison between the different shade types and control strategies should be carried out for cellular shades using a variety of control strategies in experiments and simulations.

6. REFERENCES

[1] C. Curcija, M. Yazdanian, C. Kohler, R. Hart, R. Mitchell, S. Vidanovic, Energy savings from window attachments, Lawrence Berkeley Natl. Lab. DOE/EE-0969. (2013) 102.

[2] DRI, Residential Windows and Window Coverings : A Detailed View of the Installed Base and User Behavior, 2013.

[3] N.A. Kotey, J.L. Wright, C.S. Barnaby, M.R. Collins, Solar gain through windows with shading devices: Simulation versus measurement, ASHRAE Trans. 115 PART 2 (2009) 18–30.

[4] D.C. Curcija, M. Yazdanian, C. Kohler, R. Hart, R. Mitchell, S. Vidanovic, Energy Savings from Window Attachments, (2014).

[5] EnergyPlus, EnergyPlus, (n.d.). https://energyplus.net/ (accessed February 4, 2020).

[6] LBNL, WINDOW, (n.d.). https://windows.lbl.gov/software/window (accessed August 5, 2020).

[7] ASHRAE, Measurement of Energy, Demand, and Water Savings, 2014. www.ashrae.org%0Awww.ashrae.org/technology.

[8] PNNL, Residential Prototype Building Models, (n.d.). https://www.energycodes.gov/development/residential/iecc_models (accessed January 5, 2020).

[9] AERC, Procedures for Determining Energy Performance Properties of Fenestration Attachments, (2020).

7. APPENDIX

A.1 BACKGROUND

Before developing this plan, for testing on the previous attempt (from March to May 2019), a single type of cellular shade was tested using different variations for control of the shading device as shown in Table A.1. This testing was performed using only one room in the Yarnell Station house.

Table A.1. Previous testing using a single type of cellular shade.

Control name	Control implementation	Test date
No shades	Blinds OFF (baseline) (i.e., blinds opened all the time)	Mar. 22–29, 2019
Open day	Blind ON during night (i.e., blinds opened at 7:30 am and closed at 8:00 pm	Mar. 15–22, Apr. 14–25, 2019
Closed	Blind ON 24 h	Mar. 29–Apr. 14, 2019

When overall results were observed, the case with the shades closed had a lower energy consumption while the shades opened during the day had a distribution with higher energy consumption as shown in Figure A.1.

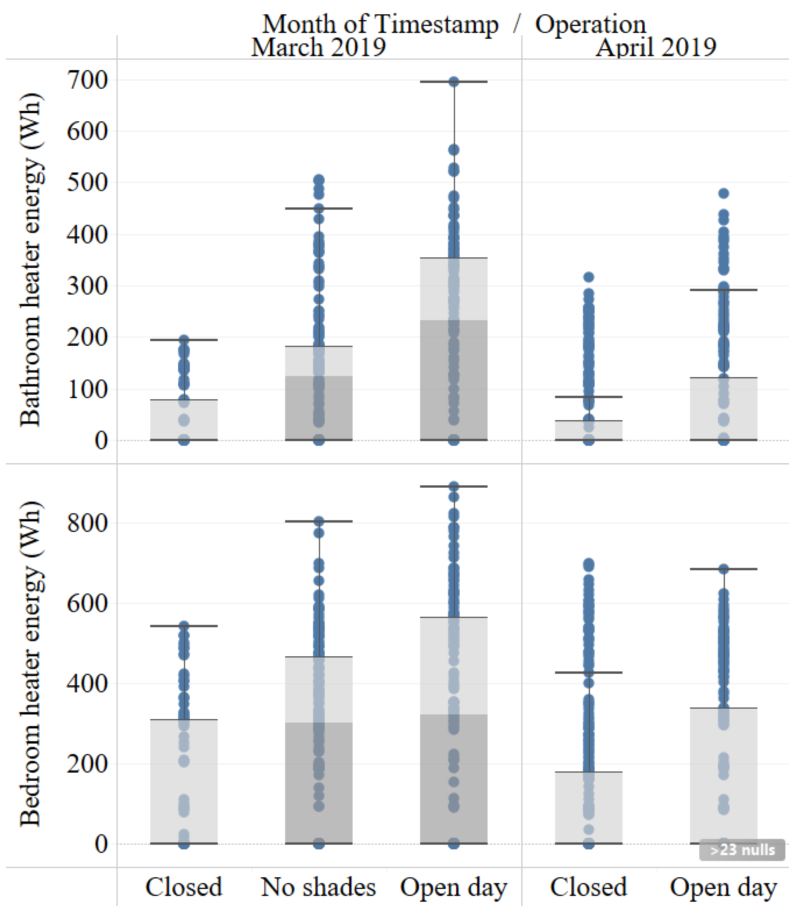

Figure A.1. Results from 2019.

However, this energy consumption can also be different from the differences in weather conditions on various test days. Therefore, we also tried to check the energy consumption when using different shade control strategies across days with similar weather by using a statistical comparison between the weather data from different days. However, even for days that were similar to each other weather-wise, the difference in energy consumption was huge; some of the times are shown in Figure A.2.

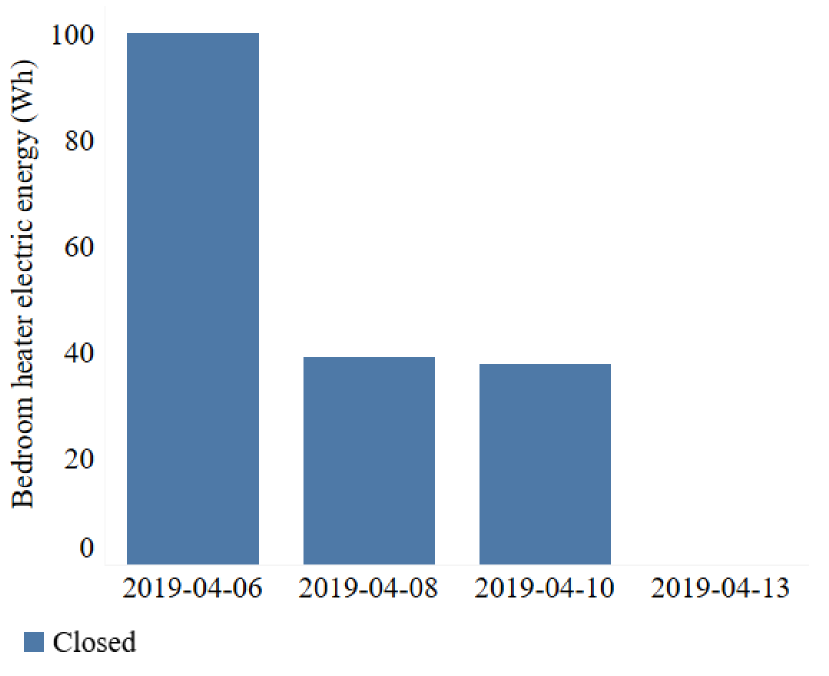

Figure A.2. Energy consumption for "Closed" control of shade during similar weather days.

In the figure, the average energy consumption for four days that were similar to one another based on a statistical comparison for the "Closed" control is shown in which two of the days (April 8 and 10, 2019) show similar energy consumption, Apr. 6, 2019 shows very high energy consumption, and April 13, 2019 shows very low energy consumption. Therefore, we decided a side-by-side testing of shading devices is needed, which led to the testing discussed in this report.

A.2 SHADE PROPERTIES WITH AERC BASELINE WINDOW

The AERC Baseline Window B – Nonmetal-framed, double pane with the following description "*The performance of attachments over all nonmetal-framed windows with double pane glazing (without low-e glass) shall be represented by the following generic wood fixed window.*
Size: 1200 mm width x 1500 mm height (exception: 1500 mm width x 1200 mm height for use with horizontal sliding storm windows and window panels)"
in [9] was used as "Baseline window".

Table A.2. Shade properties mounted on baseline window B.

Shade	**Type**	**U-factor (Btu/h·ft^2·F)**	**SHGC**	**(T_{vis})**	**EP_h**	**EP_c**
None	Baseline window*	0.481	0.763	0.814	0	0
C22	Cell-in-cell cellular (light-filtering)	0.258	0.286	0.056	9	40
C23	Cell-in-cell cellular (room-darkening; low-e)	0.222	0.207	0.000	9	47
E40	Single cell (light-filtering)	0.351	0.308	0.251	5	35
E41	Single cell (room-darkening; low-e)	0.234	0.225	0.000	8	45
SS	Single cell (room-darkening)	0.272	0.208	0	**	**
VB	Venetian blinds	0.386	0.449	0.036	−11	36

*Note: * The "Baseline window" refers to AERC Baseline Window B and should not be confused with the baseline case used in the experiment or simulations in this study. EP_h and EP_c represent the Energy Performance Index for heating, and Energy Performance Index for cooling respectively.*

****** *This product was not rated and the values are not available*

A.3 COMPARISON OF YARNELL HOUSE MEASURED AND SIMULATED DATA

Figures A.3, A.4, and A.5 provide comparisons of heater electricity consumption for Case 1, Case 2, and Case 3, respectively, used for model calibration of the Yarnell house.

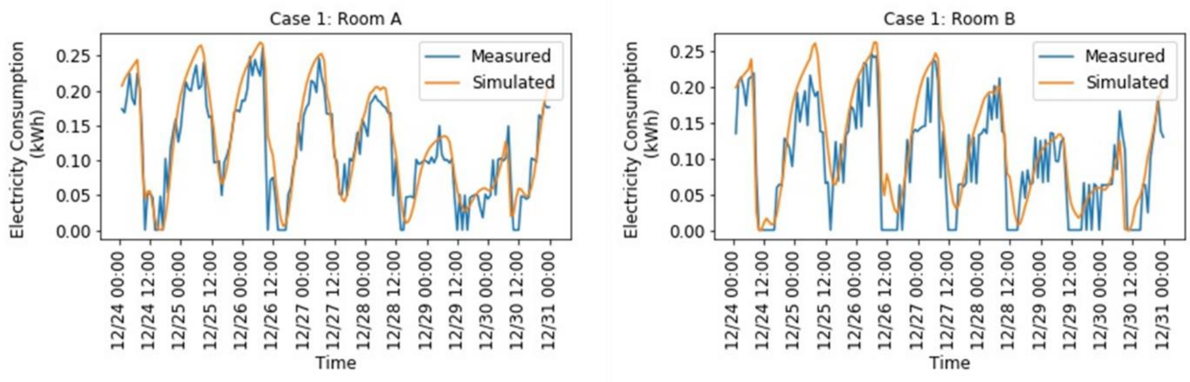

Figure A.3. Comparison of measured and simulated data at the Yarnell house, Case 1, Room A and B.

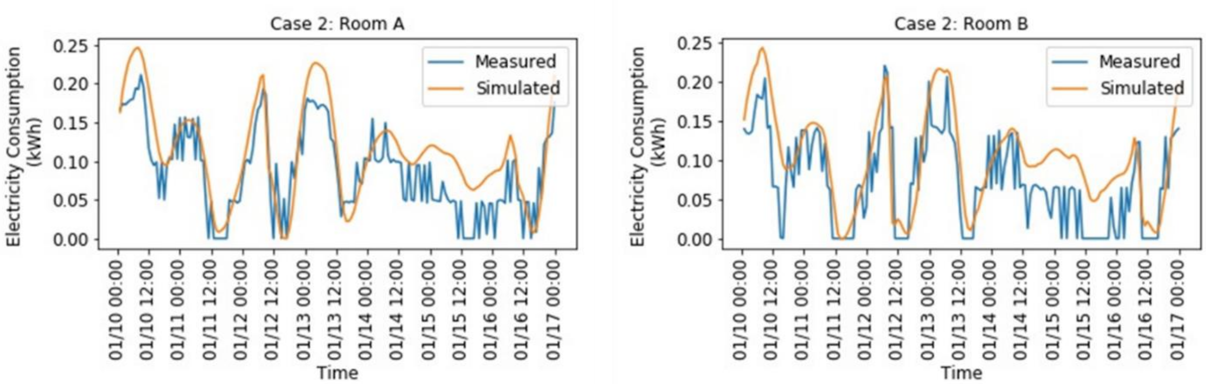

Figure A.4. Comparison of measured and simulated data at the Yarnell house, Case 2, Room A and B.

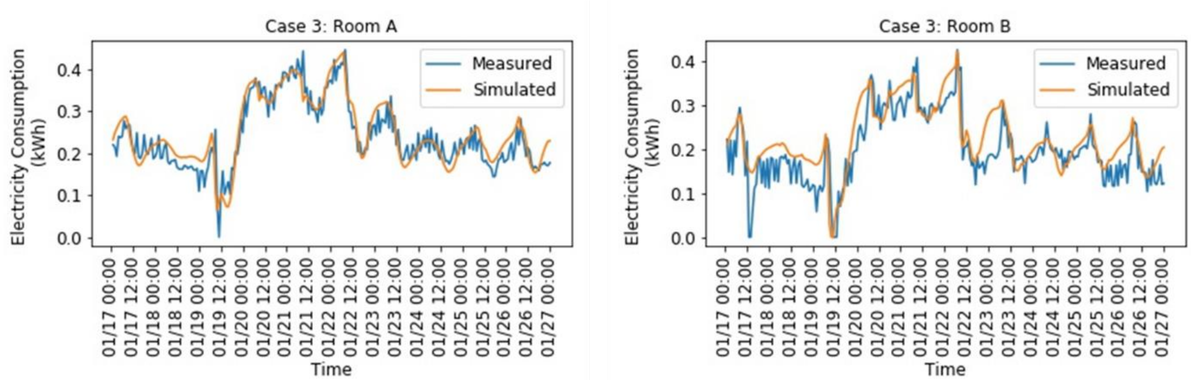

Figure A.5. Comparison of measured and simulated data at the Yarnell house, Case 3, Room A and B.

A.4 PROTOTYPE BUILDING PROPERTIES

Table A.3. Prototype building properties

Parameter	Values
Conditioned floor area	2,377 ft^2
House type	2 story-single zone
Foundation	Basement Slab-on-grade
Envelope properties	Varies based on location
Average window to wall ratio for conditioned area	12.5%
Wall area	East: 88 ft^2 West: 88 ft^2 South: 88 ft^2 North: 88 ft^2
HVAC system	Heat pump Furnace and air-conditioning
Thermostat settings	Heating: 72°F Cooling: 75°F
Internal loads	Number of people = 3 Hardwire lights = 0.34 Btu/(h·ft^2) Plug-in lights = 0.14 Btu/(h·ft^2) Refrigerator = 310 Btu/h—design level Misc. electrical equipment = 0.72 Btu/(h·ft^2) Clothes washer = 97 Btu/h—design level Clothes dryer = 727 Btu/h—design level Dish washer = 224 Btu/h—design level Range = 846 Btu/h—design level Misc. electrical load = 1,936 Btu/h—design level Plug load adjustment = 0.5 Btu/(h·ft^2)

A.5 ELECTRICITY CONSUMPTION OF CLIMATE ZONE 4A (kWh/ft^2-yr) CORRESPONDING TO Figure 12

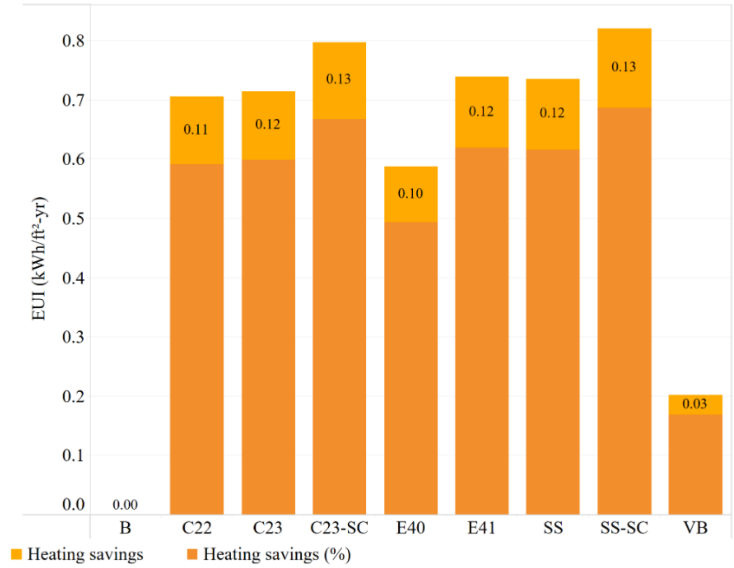

Figure A.6. Heating energy consumption and savings for a house with an unheated basement in climate zone 4A with a heat pump.

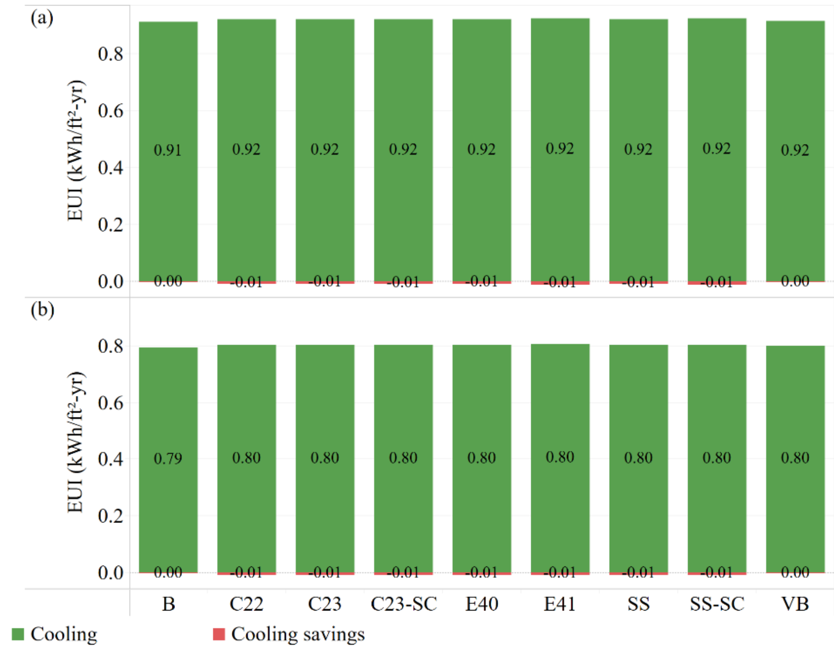

Figure A.7. Cooling energy consumption and savings for a house with an unheated basement in climate zone 4A with two different heating systems: (a) gas furnace and (b) heat pump.

A.6 SOURCE ENERGY CONSUMPTION AND SAVINGS

Error! Reference source not found. Figure A.8 provides the equivalent source energy consumption and savings for the site energy consumption shown in Figure 12, and Figure A.9 provides the corresponding energy savings in terms of source energy consumption for the site energy savings shown in Figure 13. For site to source energy conversion, a factor of 1 was used for gas and 3.3 was used for electricity.

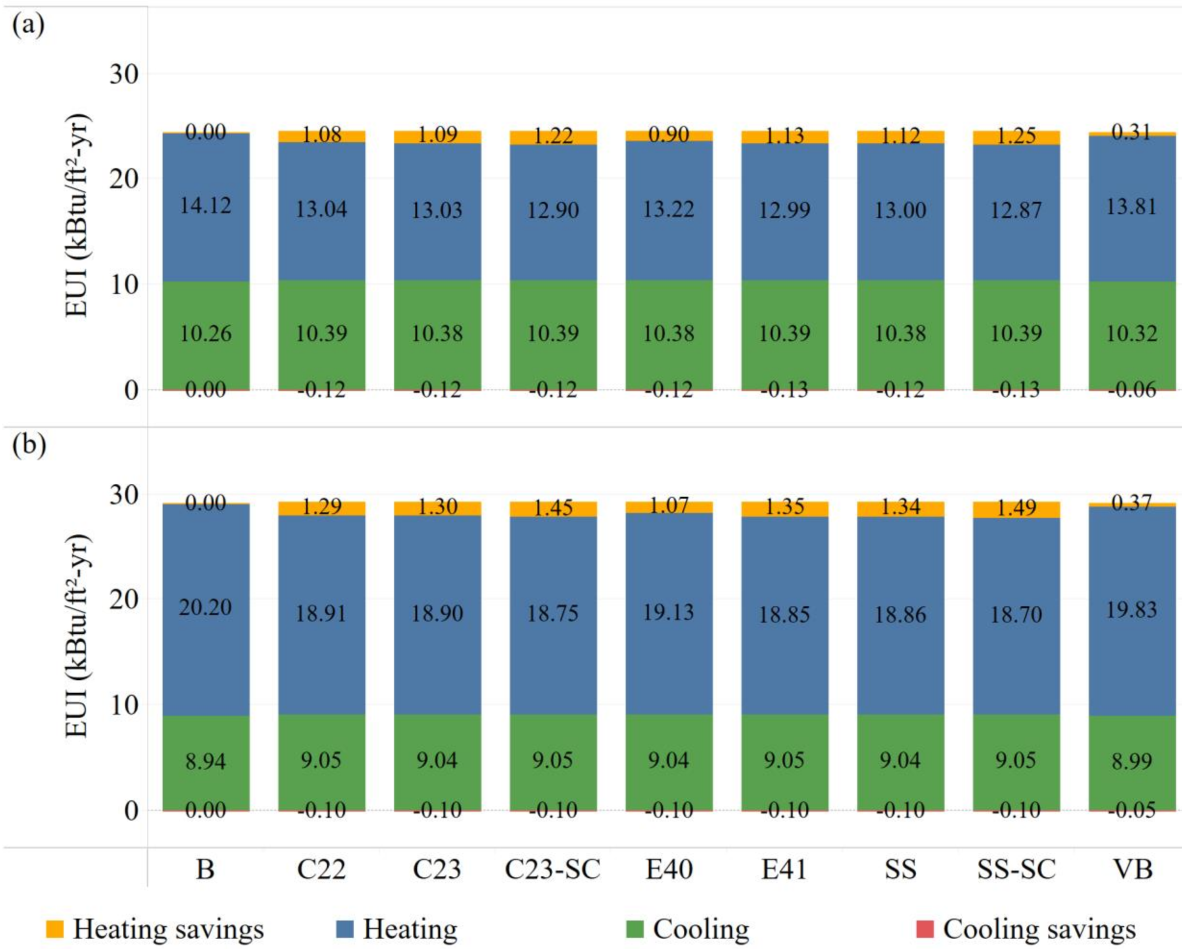

Figure A.8. Source energy corresponding to Figure 12.

		Gas furnace								Heat pump							
		C22	C23	C23-SC	E40	E41	SS	SS-SC	VB	C22	C23	C23-SC	E40	E41	SS	SS-SC	VB
Slab	1A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1
	2A	0.6	0.6	0.6	0.4	0.6	0.6	0.7	0.1	0.5	0.6	0.6	0.4	0.6	0.6	0.6	0.1
	2B	0.7	0.7	0.7	0.5	0.7	0.7	0.8	0.1	0.6	0.6	0.7	0.5	0.6	0.7	0.7	0.1
	3A	0.7	0.8	0.8	0.6	0.8	0.8	0.9	0.1	0.8	0.8	0.9	0.6	0.8	0.8	0.9	0.1
	3B	0.6	0.6	0.7	0.5	0.6	0.6	0.7	0.1	0.5	0.5	0.6	0.4	0.6	0.6	0.6	0.1
	3C	0.9	0.9	1.0	0.7	0.9	0.9	1.0	0.2	0.7	0.7	0.8	0.6	0.8	0.7	0.8	0.2
	4A	1.1	1.1	1.3	0.9	1.2	1.2	1.3	0.2	1.4	1.4	1.5	1.1	1.4	1.4	1.6	0.3
	4B	1.0	1.0	1.1	0.8	1.1	1.1	1.2	0.2	1.0	1.0	1.1	0.8	1.1	1.1	1.2	0.2
	4C	1.2	1.2	1.3	0.9	1.2	1.2	1.3	0.3	1.3	1.3	1.4	1.0	1.3	1.3	1.5	0.3
	5A	1.4	1.5	1.7	1.1	1.5	1.5	1.7	0.3	2.3	2.4	2.7	1.8	2.4	2.4	2.8	0.4
	5B	1.3	1.3	1.5	1.1	1.4	1.4	1.5	0.3	1.6	1.6	1.8	1.3	1.7	1.7	1.9	0.4
	6A	1.6	1.6	1.8	1.2	1.7	1.7	1.9	0.3	2.9	2.9	3.3	2.2	3.0	3.0	3.4	0.5
	6B	1.7	1.7	1.9	1.3	1.8	1.8	2.0	0.4	2.7	2.7	3.0	2.2	2.8	2.8	3.1	0.6
	7	2.1	2.1	2.4	1.6	2.2	2.2	2.5	0.4	4.2	4.3	4.9	3.3	4.4	4.4	5.0	0.8
	8	2.5	2.6	2.9	1.9	2.6	2.6	3.0	0.4	5.7	5.8	6.7	4.3	6.0	5.9	6.8	0.9
Unheated basement	1A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1
	2A	0.5	0.5	0.5	0.4	0.5	0.5	0.6	0.1	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.1
	2B	0.6	0.6	0.6	0.5	0.6	0.6	0.6	0.1	0.5	0.5	0.6	0.4	0.6	0.6	0.6	0.1
	3A	0.6	0.6	0.7	0.5	0.6	0.6	0.7	0.2	0.7	0.7	0.8	0.5	0.7	0.7	0.8	0.2
	3B	0.5	0.5	0.5	0.4	0.5	0.5	0.6	0.1	0.4	0.4	0.5	0.4	0.5	0.5	0.5	0.1
	3C	0.7	0.7	0.8	0.6	0.8	0.8	0.8	0.3	0.6	0.6	0.7	0.5	0.6	0.6	0.7	0.2
	4A	1.0	1.0	1.1	0.8	1.0	1.0	1.1	0.3	1.2	1.2	1.4	1.0	1.2	1.2	1.4	0.3
	4B	0.8	0.9	0.9	0.7	0.9	0.9	1.0	0.3	0.9	0.9	1.0	0.7	0.9	0.9	1.0	0.3
	4C	1.0	1.0	1.1	0.8	1.0	1.0	1.1	0.3	1.1	1.1	1.2	0.9	1.1	1.1	1.3	0.3
	5A	1.2	1.3	1.4	1.0	1.3	1.3	1.5	0.3	2.0	2.1	2.3	1.6	2.1	2.1	2.4	0.5
	5B	1.1	1.2	1.3	1.0	1.2	1.2	1.3	0.3	1.4	1.4	1.6	1.2	1.5	1.5	1.6	0.4
	6A	1.4	1.4	1.6	1.1	1.5	1.5	1.6	0.4	2.5	2.5	2.8	2.0	2.6	2.6	2.9	0.7
	6B	1.5	1.5	1.6	1.2	1.5	1.5	1.7	0.4	2.3	2.4	2.6	1.9	2.4	2.4	2.7	0.7
	7	1.8	1.8	2.1	1.5	1.9	1.9	2.1	0.5	3.7	3.8	4.3	3.0	3.9	3.9	4.4	1.0
	8	2.2	2.3	2.6	1.8	2.4	2.3	2.7	0.6	5.0	5.1	5.9	4.0	5.3	5.2	6.0	1.2

Total savings (kBtu/ft²-yr)

-0.1 … 6.8

Figure A.9. Source energy savings corresponding to Figure 13.

A.7 TOTAL SITE ENERGY SAVINGS WHEN SHADE ARE ALWAYS CLOSED

The total site energy savings using the different types of cellular shades in "Always Closed" position is shown in Figure A.10 and A.11 in absolute and relative terms respectively. The energy simulations across different climate zones showed that total energy savings of up to 3.9 kBtu/ft^2-yr can be achieved from heating and cooling from the use of cellular shades. Generally, using this strategy the energy savings was higher in cooling dominated climate and lower in heating dominated climate compared to the strategy where the shades were closed during night hours. This is because of reduction of solar heat gain from closing the shaded during the daytime. In terms of the percentage savings, the energy savings using cellular shades when closed for 24 hours were up to 15% for total energy from heating and cooling similar to the closed during night hours with savings increased in hot climate and decreased in cold climate. The exception to this is climate zone 8 where the energy savings increased even if it's cold climate.

Always Closed

		Gas furnace							Heat pump						
		C22	C23	C23-SC	E40	E41	SS	SS-SC	C22	C23	C23-SC	E40	E41	SS	SS-SC
Slab	1A	1.0	1.1	1.2	0.9	1.1	1.2	1.3	1.0	1.1	1.1	0.8	1.1	1.1	1.2
	2A	1.3	1.4	1.5	1.1	1.4	1.4	1.5	0.9	1.0	1.1	0.8	1.0	1.0	1.1
	2B	1.7	1.7	1.9	1.4	1.8	1.8	1.9	1.3	1.4	1.5	1.1	1.4	1.5	1.6
	3A	1.2	1.2	1.4	1.0	1.3	1.3	1.4	0.8	0.8	0.9	0.7	0.8	0.9	0.9
	3B	1.1	1.1	1.2	0.9	1.2	1.1	1.2	0.8	0.8	0.9	0.7	0.8	0.8	0.9
	3C	1.0	1.0	1.1	0.9	1.0	1.0	1.0	0.4	0.4	0.5	0.4	0.4	0.4	0.5
	4A	1.2	1.1	1.3	0.9	1.2	1.0	1.2	0.9	0.9	1.0	0.7	0.9	0.9	1.0
	4B	1.2	1.1	1.2	0.9	1.2	1.0	1.1	0.9	0.9	1.0	0.8	0.9	0.9	1.0
	4C	1.5	1.4	1.6	1.2	1.5	1.4	1.6	0.8	0.8	0.9	0.7	0.8	0.8	0.9
	5A	1.6	1.5	1.8	1.2	1.6	1.5	1.8	1.1	1.1	1.3	0.9	1.2	1.1	1.3
	5B	1.5	1.4	1.6	1.1	1.5	1.4	1.5	1.0	1.0	1.1	0.8	1.0	1.0	1.1
	6A	1.7	1.6	1.8	1.2	1.7	1.5	1.8	1.2	1.2	1.4	0.9	1.3	1.2	1.4
	6B	1.5	1.4	1.6	1.1	1.5	1.3	1.5	1.1	1.1	1.2	0.9	1.2	1.1	1.2
	7	2.1	1.9	2.3	1.5	2.1	1.8	2.2	1.6	1.5	1.8	1.2	1.6	1.5	1.8
	8	3.4	3.3	3.9	2.5	3.5	3.3	3.9	2.7	2.7	3.2	2.0	2.8	2.8	3.2
Unheated basement	1A	0.9	1.0	1.1	0.8	1.0	1.0	1.1	0.9	1.0	1.0	0.8	1.0	1.0	1.1
	2A	1.1	1.2	1.3	1.0	1.2	1.2	1.3	0.8	0.9	0.9	0.7	0.9	0.9	1.0
	2B	1.5	1.5	1.6	1.2	1.5	1.6	1.7	1.2	1.3	1.4	1.0	1.3	1.3	1.4
	3A	1.1	1.1	1.2	0.9	1.1	1.1	1.2	0.7	0.7	0.8	0.6	0.8	0.8	0.8
	3B	1.0	1.0	1.0	0.8	1.0	1.0	1.0	0.7	0.7	0.8	0.6	0.7	0.8	0.8
	3C	0.8	0.8	0.9	0.8	0.9	0.8	0.9	0.4	0.4	0.4	0.3	0.4	0.4	0.4
	4A	0.9	0.8	1.0	0.7	0.9	0.7	0.9	0.7	0.8	0.8	0.6	0.8	0.8	0.9
	4B	0.9	0.7	0.8	0.7	0.8	0.7	0.8	0.8	0.8	0.8	0.7	0.8	0.8	0.9
	4C	1.2	1.1	1.3	1.0	1.2	1.1	1.3	0.7	0.7	0.8	0.6	0.7	0.7	0.8
	5A	1.3	1.2	1.4	1.0	1.3	1.2	1.4	1.0	1.0	1.1	0.8	1.0	1.0	1.1
	5B	1.2	1.1	1.2	1.0	1.2	1.1	1.2	0.8	0.8	0.9	0.7	0.9	0.9	1.0
	6A	1.3	1.2	1.5	1.0	1.3	1.2	1.4	1.0	1.0	1.2	0.8	1.1	1.0	1.2
	6B	1.2	1.0	1.2	0.9	1.1	1.0	1.2	0.9	0.9	1.0	0.8	1.0	0.9	1.0
	7	1.6	1.5	1.8	1.2	1.6	1.4	1.8	1.3	1.3	1.5	1.0	1.4	1.3	1.5
	8	2.9	2.8	3.4	2.3	3.0	2.8	3.4	2.4	2.4	2.8	1.9	2.5	2.4	2.8

Total savings (kBtu/ft^2-yr)

0.3 – 3.9

Figure A.10. Absolute energy savings for different combinations of heating systems and foundation types for all cellular shades and climate zones

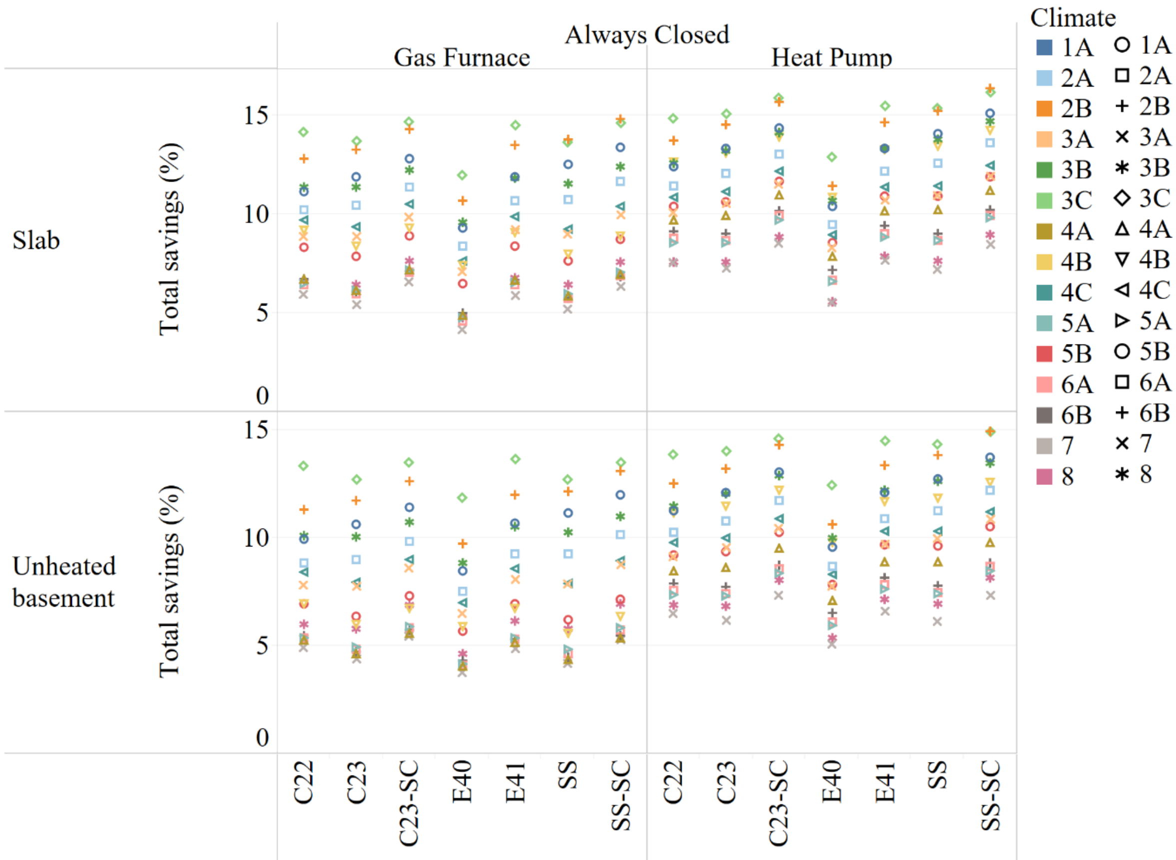

Figure A.11. Relative total energy savings for different combinations of heating systems and foundation types for all cellular shades and climate zones

A.8 RELATIVE ENERGY SAVINGS FOR ALL DIFFERENT CASES

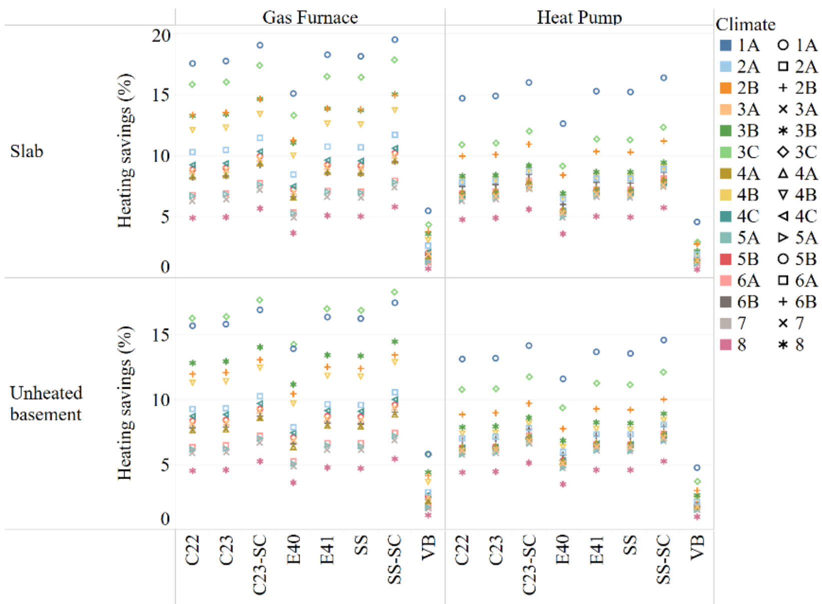

Figure A.12. Relative heating energy savings for different combinations of heating systems and foundation types for all shade and climate zones.

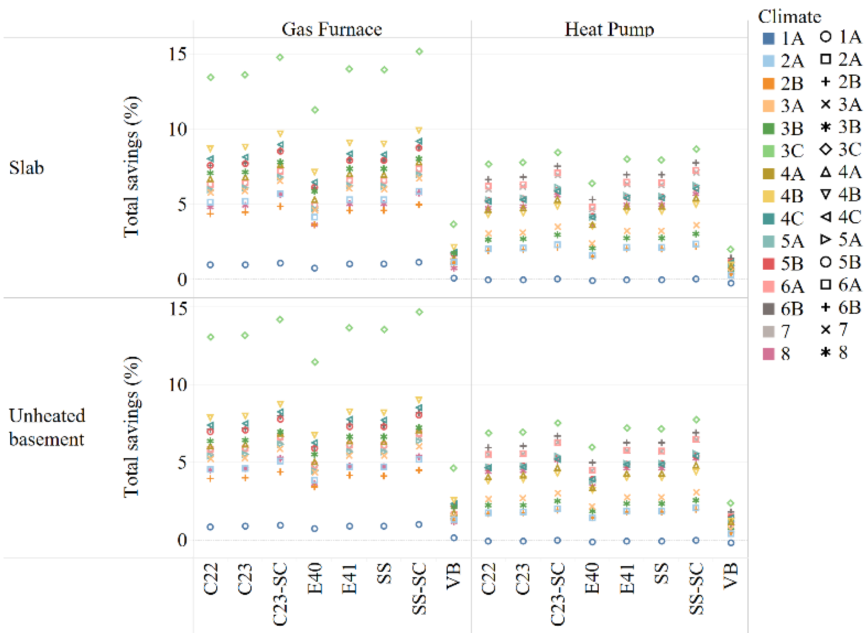

Figure A.13. Relative total energy savings for different combinations of heating systems and foundation types for all shade and climate zones.