



Modeling Cellular Shades in EnergyPlus

December 2017

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Prepared for
the Silicon Valley Power
under Strategic Partnership Projects

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Richland, Washington 99352

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Executive Summary

Laboratory and field studies have demonstrated that the use of window attachments such as cellular shades can provide significant savings by reducing energy consumed for heating, cooling, and ventilation in homes. The degree to which this measure saves energy, however, depends on a number of factors including the type of attachment, the structural and orientation characteristics of the home, the characteristics of primary window on which it is attached, climate conditions, and operating schedules. This report, sponsored by Silicon Valley Power and the American Public Power Association's Demonstration of Energy and Efficiency Developments Program, examines the savings potential of cellular shades in 13 climate zones throughout California and the United States. The energy savings are modeled using EnergyPlus simulation software and include savings for three different prototype homes, two variations of window types and window area, and two different types of cellular shades. The results from this study will be valuable input for utility incentive programs around the United States.

The shading schedule implemented for this study is seasonal and results in close-to-optimal results. Shades are modeled as always down from April to September (simplified cooling season). They are modeled as up during the day (6:00 a.m. to 6:00 p.m.) and down at night (6:00 p.m. to 6:00 a.m.) from October to March (simplified heating season).

The results demonstrate year-round heating and air conditioning savings in all cases and climate zones examined. According to these models, double-cell shades provide nearly the same energy savings as triple-cell shades. Savings are most significant in smaller, existing homes with relatively high window-to-wall ratios. For these home types, energy savings associated with operating heating, ventilation, and air conditioning ranges from 10% to 34%. For this study, the simulated saving results depend on specific shading schedules. It is not likely that an occupant would precisely follow these schedules manually; however, there are options for automating shading controls for more persistent savings.

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This project required extensive collaboration from outside stakeholders, and the authors greatly appreciate the efforts of all the people who were involved in successful completion of the work. The authors acknowledge Mudit Saxena of Vistar Energy Consulting for his technical assistance and persistence with the WINDOW modeling software. Charlie Curcija of Lawrence Berkeley National Laboratory shared his previous work and helped verify certain assumptions made for this study. Greg Sullivan of Efficiency Solutions and Joshua McIntosh and Travis Ashley of Pacific Northwest National Laboratory also played key roles in providing historical and current weather and Lab Homes data used to calibrate the models. Finally, this work would not have been possible without the funding support provided by Silicon Valley Power and the American Public Power Association's Demonstration of Energy and Efficiency Developments Program.

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Acronyms and Abbreviations

DOE	U.S. Department of Energy
EMS	Energy Management System
HVAC	Heating, ventilation, and air conditioning
LBNL	Lawrence Berkeley National Laboratory
PNNL	Pacific Northwest National Laboratory

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1.0 Introduction

Residential buildings in the United States currently require approximately 8 quadrillion Btu/yr of energy for heating and cooling, which accounts for about 40% of the primary energy consumed by homes.¹ Windows are a major contributor to heat losses (and gains) in residential buildings. For example, past studies demonstrated that windows account for approximately 25% of the heating, ventilation, and air conditioning (HVAC) energy use in a typical residential building (Huang et al. 1999). Energy-efficient window attachments, such as insulated cellular shades, appear to have potential for effectively reducing energy consumption resulting from HVAC operation in new and existing buildings. Because of the relative affordability of window attachments that can be easily installed to save energy in both new and existing homes, a significant opportunity exists to provide energy savings by promoting the appropriate use of energy-efficient window attachments. Determining the appropriate use and applications of these window attachments, however, will depend on seasonal and climate factors and the thermal characteristics of the home and the installed attachments. This study examines the energy performance of double-cell insulating cellular shades in residential buildings in multiple climate zones with multiple operation schemes.

1.1 Window Attachment Development and Previous Research

In 2013, the U.S. Department of Energy (DOE) sponsored a comprehensive energy modeling study led by Lawrence Berkeley National Laboratory (LBNL). This study focused on a range of window attachments, including products such as shades, blinds, storm window panels, and surface-applied films. Energy modeling was simulated in four types of “typical” houses located in 12 characteristic climate zones. The simulations captured the optical and thermal complexities of these products (Curcija et al. 2013). They also considered typical operation and usage patterns based on a separate study focusing on user behavior with respect to operable window coverings (Bickel et al. 2013). The study found that many of the window attachments examined can yield significant energy savings when installed over windows. However, the degree of savings depends on the attachment type, baseline window conditions, seasonal and climate factors, and when applicable, how the attachment is operated. Nevertheless, the study concluded that a number of window attachments offer year-round savings in several climate zones.

In addition to DOE research focused on window coverings, a number of research institutions, energy efficiency programs, and utilities have completed characterization and meta analyses² (Ariosto et al. 2013) and energy simulation analyses (CEE 2014; Garber-Slaght and Craven 2011; Zirmhelt et al. 2015). These studies validated energy savings from cellular shades and other window attachments in multiple climate zones and prototype residential buildings. Some field studies also examined energy savings from cellular shades over aluminum-framed clear-glass windows (PGE 2015).

Whole-home experiments for triple-cell opaque cellular shades³ were conducted using two factory-built side-by-side “Lab Homes” located at Pacific Northwest National Laboratory (PNNL) in Richland, Washington (Petersen et al 2016). These experiments measured the potential energy savings of window attachment products at different operational schedules in an experimental home compared to a control home equipped with standard double-pane, clear-glass windows with aluminum frames and sliding clear-

¹ Based on 2017 Annual Energy Outlook (years 2015–2017) reference case heating and cooling primary end use consumption from “Table 4. Residential sector key indicators and consumption.” Annual Energy Outlook (DOE). Available online: https://www.eia.gov/outlooks/aeo/tables_ref.php

² See, for example, the website: <http://www.efficientwindowcoverings.org/>, sponsored and developed by DOE, Building Green, and LBNL and DOE’s <http://energy.gov/energysaver/articles/energy-efficient-window-treatments>.

³ Hunter Douglas Duette ® Architella ® Trielle™ shades.

glass patio doors. The windows in the control home are representative of those installed in many existing homes in the western regional states and much of the United States. Different operational schedules were tested to help understand the effect of the window attachment technology on HVAC energy use. The results of the experiments demonstrated energy savings during both the heating and cooling seasons when operated optimally,⁴ Results of these studies also revealed energy savings in both seasons when attachments were closed compared to standard vinyl horizontal Venetian blinds (see Table 1).

Table 1. Lab Homes Cellular Shade Experiments 2015–2016 (triple-cell cellular shades).
(Source: Petersen et al. 2016)

Experiment	Sponsor	Window baseline description	Findings ^a
Whole-House Laboratory Experiments			
Triple-Cell Cellular Shades (operated optimally)	DOE, BPA, ^b Hunter Douglas	Double-pane aluminum-frame clear glass (no window attachments in control home)	<ul style="list-style-type: none"> • Cooling savings 14.8 ±2.1%^c • Heating savings 14.4% ±2.0%
Triple-Cell Cellular Shades (always drawn down)	DOE, BPA, Hunter Douglas	Double-pane aluminum-frame clear glass (venetian blind attachments in control home always down)	<ul style="list-style-type: none"> • Cooling savings 16.6±2.9% • Heating savings 10.5±3.0%

^a Based on a 95% confidence interval.
^b Bonneville Power Administration.

These promising field tests and studies formed the basis for further examination with simulated energy models developed to determine the energy savings potential of high efficiency cellular shades in multiple climate zones.

1.2 Project Scope

This project builds on DOE-sponsored research PNNL in which energy savings from cellular shading devices were determined using PNNL’s Lab Homes. Data from the PNNL Lab Homes were used to calibrate the cellular shades model in EnergyPlus. Certain details of the model were changed to help calculate a range of savings estimates, based on a wide range of inputs. Variables considered in this study are listed below:

- Thirteen climate zones
- Three prototype home layouts
- Two variations of window area
- Two window types (including one representing new homes, and one representing existing homes)
- Two cellular shade performance levels.

⁴ Where “optimal” operation was based the Hunter Douglas “Green Mode” schedule, which is designed to maximize the energy savings from insulated window shades while maintaining views to the outdoors during daylight hours.

2.0 Model Calibration

Typical model calibration involves using experimental data to verify that performance calculations simulated by a model for a certain technology provide results consistent with actual technology performance measured in the field. Once a model is calibrated against real data, it can be tweaked to determine the energy use of that technology under different scenarios. The energy characteristics of the PNNL Lab Homes are well characterized, and power consumption during tests is metered in detail. This makes the homes a useful platform for calibrating energy simulation models. The simulated building energy consumption is calibrated to the actual building energy consumption measured in the Lab Homes, both with and without the use of cellular shades.

Model calibration for cellular shades involved updating the structure of a previously developed Lab Homes model so it could simulate the HVAC performance with cellular shades. As with any model development task, after initial calibration results are found, modifications need to be made to the software. This modification step ensures the most realistic parameters are being used to provide the most accurate results. The final calibration parameters and results for the energy model are described in Sections 2.1 and 2.2 of this report.

2.1 Lab Homes Model Assumptions

The side-by-side Lab Homes at PNNL allow energy-saving and grid-responsive technologies to be tested precisely in a controlled environment. Because of this side-by-side orientation, the homes experience the same weather and solar conditions. Each Lab Home has seven windows and two sliding glass doors, for a total of 196 ft² of window area. For the experiments modeled in this study, the “experimental home” was retrofitted with Hunter Douglas honeycomb shades,⁵ while a matching “control home” was equipped with no window coverings. The floor plan of the Lab Homes, as constructed, is shown in Figure 1.

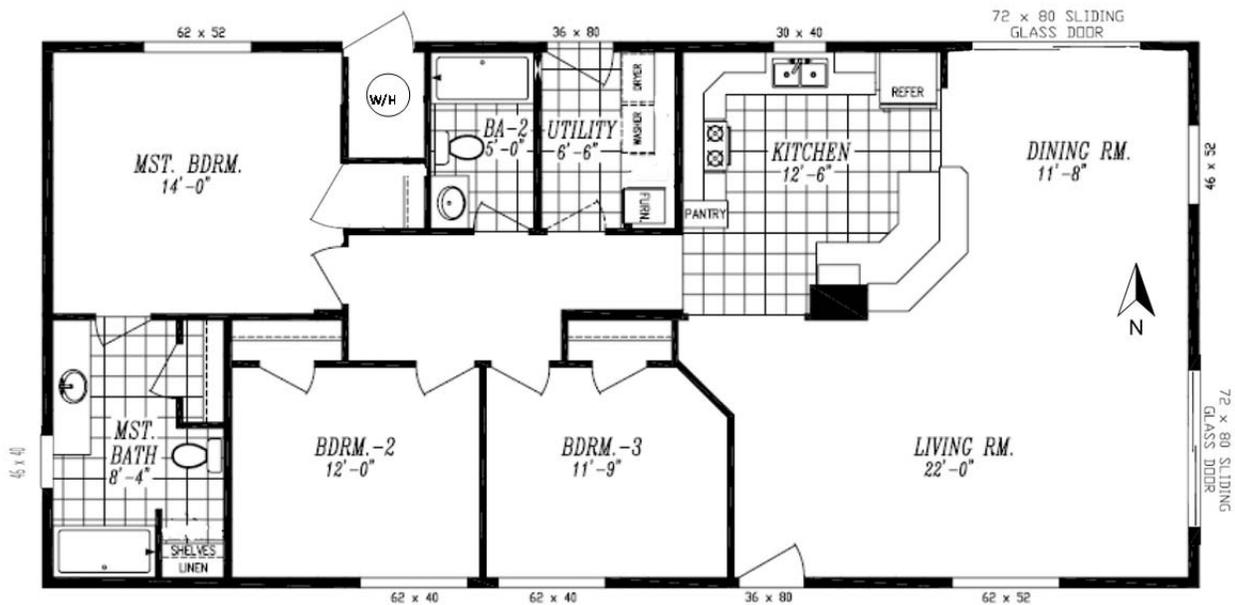


Figure 1. Floor Plan of the Lab Homes as Constructed

⁵ Hunter Douglas Duette Architella honeycomb shades

The following physical parameters of the PNNL Lab Homes were modeled:

- Cooling system: Heat Pump, 13 Seasonal Energy Efficiency Ratio, 8.0 Heating Seasonal Performance Factor, 2.5 ton
- Heating system: two-element electric forced air furnace
- Air handler: four speeds, 4 ton, one-third horsepower, 2.9 full-load amp rating
- True lighting, occupancy, and equipment load schedule based on experimental data
- Thermostat set points of 76°F for the cooling period and 85°F for the heating period due to mild temperatures
- Air leakage input based on recent air infiltration testing results.

The following modeling assumptions were used in addition to the physical parameters:

- Real weather conditions (i.e., outdoor air dry bulb temperatures and horizontal solar radiation) collected under the experimental period were used for the simulation.
- Other weather parameters, such as outdoor air wet bulb temperature and wind speeds, are assumed to be the same as the typical meteorological year.
- All windows were modeled using Construction: *ComplexFenestrationState* object⁶ that is generated using the latest version of WINDOW v7.5.38.0 and THERM v7.5.18.0 software.⁷
- All models were created using EnergyPlus v8.8.⁸

2.2 Results of Model Calibration

The model calibration exercise focused on specific days for which a complete set of data from the Lab Homes experiments was available, including outdoor solar irradiance values. The calibration days also focused on particularly hot or cold days, in order to ensure that there was a substantial indoor/outdoor temperature difference, which helped make the HVAC signal much clearer. The dates used for model calibration included June 19 and 20, 2017, for the cooling season and September 22 through 26, 2017, for the heating season. The daily high temperatures for June 19 and 20 were 91.9°F and 89.1°F, respectively. The daily temperature lows for September 22 through 26th were 44.1°F, 48°F, 46.9°F, 48.9°F, and 53.1°F, respectively. Another cellular shades experiment was underway at the same time data for this study was collected. Care was taken to ensure that adequate results were obtained to provide bases for conclusions drawn for both projects.

The results of this exercise are provided in Tables 2 and 3 below. Table 2 provides the total energy use over the experimental days, and Table 3 provides the percent difference of the two values.

⁶ This is the most complex window modeling method. It provides a layer-by-layer physical description of the fenestration system in the EnergyPlus model programming.

⁷ See LBNL “Windows & Daylighting” website resource for more information on software tools: <https://windows.lbl.gov/software/therm>.

⁸ EnergyPlus is a whole building energy simulation program developed with support from DOE: <https://energyplus.net/>.

Table 2. Energy Use during Experimental Days

Control or Experimental Home	With or Without Shades	Season	Experimental (Actual) HVAC Energy Use (kWh)	Experimental (Actual) Total Energy Use (kWh)	Modeled HVAC Energy Use (kWh)	Modeled Total Energy Use (kWh)
Control	Without	Cooling	48.7	75.2	46.3	72.7
Experimental	With	Cooling	35.2	63.6	30.5	58.8
Control	Without	Heating	83.1	157.8	92.3	166.0
Experimental	With	Heating	102.1	176.2	117.3	190.7

Table 3. Percent Difference between Measured Energy Consumption and Modeled Energy Consumption

Control or Experimental Home	With or Without Shades	Season	HVAC % Difference (actual-modeled HVAC consumption)	Whole-House % Difference (actual-modeled whole-house energy consumption)
Control	Without	Cooling	5%	3%
Experimental	With	Cooling	15%	8%
Control	Without	Heating	-10%	-5%
Experimental	With	Heating	-13%	-8%

Table 4 shows the predicted savings of the experiment and the model separately. In all cases, energy savings are calculated using the energy use with shades, minus the energy use without shades, divided by the energy use without shades. It is worth noting that during the heating season, when the shades are down for the entire day, savings are negative for the days examined during the calibration period (see Table 4, heating season results). This means that the home with the cellular shades fully drawn down was consuming more HVAC because the shades were blocking beneficial solar heat gains. This effect was appropriately captured in both the experimental field data and the simulated modeled data. Table 4 shows that the model is over-predicting the whole-house energy *savings* by a mere 4%⁹ in the cooling season, and over-predicting the energy *penalty* by about 3% in the heating season. These results are in good agreement and ensure that the cellular shades part of the model can be used to help extrapolate potential energy savings information from a much wider range of buildings.

Table 4. Predicted Savings: Experiment vs. Model

Type of Savings Due to Shades	Season	Percent Savings between Two Homes (HVAC only)	Percent Savings between Two Homes (whole house)
Experiment	Cooling	28%	15%
Model	Cooling	34%	19%
Experiment	Heating	-23%	-12%
Model	Heating	-27%	-15%

⁹ Modeled cooling savings of 19% minus experiment savings of 15% equals 4%.

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3.0 Parametric Model Setup

All parametric models were simulated with EnergyPlus v8.8 using the PNNL supercomputer (known as the PNNL Institutional Computing program, or PIC). Challenging aspects of the parametric setup include developing the complex window objects, determining the general model assumptions, and developing an Energy Management System (EMS) workaround strategy for scheduling the on/off state of the complex window objects.

3.1 Complex Window Objects

Windows and shades were modeled as complex fenestration construction objects using the latest version of WINDOW v7.5.38.0 and THERM v7.5.18.0 software. Complex fenestration construction objects include the window and shade together. Thus, four complex window objects were required for this study. The four objects included the following combinations:

- U-factor of 0.32 window with double-cell cellular shades
- U-factor of 0.32 window with triple-cell cellular shades
- U-factor of 0.68 window with double-cell cellular shades
- U-factor of 0.68 window with triple-cell cellular shades.

The following assumptions were made when developing the complex window objects for the parametric study:

- Windows with a U-factor of 0.32 were assumed to be double-pane, low-e on a vinyl frame with an air gap of 0.5 inches.
- Windows with a U-factor of 0.68 were assumed to be double-pane, clear glass with an aluminum frame (with a break).
- Double-cell cellular shades were assumed to be fabric type C22 – semi-opaque, production fit, with edge gaps of 0.276 in., 0.172 in., 0.135 in., and 0.067 in. on the left, right, top, and bottom sides, respectively. The pleat size for this shade was assumed to be 0.75 in. with an inner wall length of $\frac{6}{16}$ in. and a cell height between 0.5 and 0.75 in.

3.2 Modeling Assumptions

In addition, the following assumptions were used for all the models in the parametric study:

- The cooling system was assumed to be an air conditioner with Seasonal Energy Efficiency Ratio 13 rating, and the heating system was assumed to be an electric furnace in all cases.
- The window area was distributed evenly around all four sides of the building to create a solar-neutral configuration.
- Shades were modeled as always down from April 1 to September 30 to optimize performance during the cooling season.

- Shades were modeled as all-the-way-up (providing no shading) from 6:00 a.m. to 6:00 p.m., and all-the-way-down from 6:00 p.m. to 6:00 a.m. from October 1 to March 30 (i.e., the heating season). This simplified schedule was intended to produce savings during the heating season by allowing beneficial heat gains into the home during the day and reducing heat losses during the night. Because this schedule has no shading (i.e., shades pulled up) during several hours when no beneficial daylight and heat gains are available (e.g., during the early morning and early evening), it would *not* be considered optimal from an energy perspective. However, this schedule was selected because it should capture at least some savings and could easily be understood and implemented by a homeowner. It also provides a straightforward schedule modeling purposes.

Other assumptions made for all of the parametric models were:

- Plug loads and lighting assumptions following the rules used by the simulation-based performance path in the International Energy Conservation Code (IECC) (ICC 2018).
- The cooling set point was 75°F and the heating set point was 72°F. Both were enabled simultaneously, so cooling and heating could presumably be called for in the same day if the indoor temperature moved outside of that band.
- Six time steps were assumed per hour in the simulation leading to a time step of 10 minutes.

3.3 Energy Management System Workaround for Scheduling Complex Window Objects

As mentioned earlier, the detailed performance of the window and shade was captured using the EnergyPlus Complex Fenestration Construction object. EnergyPlus allows coupling each window object with one complex fenestration construction object for the entire simulation period. However, the model assumptions required simulating two different window shade configurations that depending on the season and the hour of the day, led to two different complex fenestration construction objects. To work around this limitation, the advanced EMS feature was employed. EMS provides a way to develop custom control and modeling routines and can be harnessed by writing a special computer program in the EnergyPlus Runtime Language to describe control algorithms. The program is then read and executed as the model is being run. Thus, EMS provides high-level, supervisory control to override selected aspects of EnergyPlus modeling (EnergyPlus 2017).

The window and shade operating schedule is implemented by writing an EnergyPlus Runtime Language program that switches the window construction between fully shaded and a fully open configurations based on the month and the hour of the day. The month and hour are captured within a given time step and available as special EMS variables, making the implementation robust. In addition, sensitivity testing comparing results from the EMS test cases and the non-EMS test cases yielded an excellent match.

4.0 Parametric Modeling Variables

The variables described in this chapter provide details for the parametric study conducted that resulted in more than 400 simulations. This diversity allows utilities and other researchers to pick and choose which modeling results apply to their housing stock and extrapolate potential savings estimates accordingly. Results from these parametric simulations are presented in Chapter 5.

4.1 Climate Zones

Thirteen climate zones were chosen to help represent a reasonable distribution of potential energy savings in California and across the United States. Table 5 shows the typical meteorological year-3 locations used, as well as the categorization of California, IECC and DOE Building America climate zones associated with the locations.

Table 5. Thirteen Climate Zones Used For the Sensitivity Study

Simulation Location	California Climate Zone	IECC Climate Zone	DOE Building America Climate Zone
Miami, FL	N/A	1A	Hot-Humid
Houston, TX	N/A	2A	Hot-Humid
Imperial County Airport, CA	15	2B	Hot-Dry
Sacramento Metro Airport, CA	12	3	Hot-Dry
Burbank – Glendale, CA	9	3	Hot-Dry
San Diego – Lindbergh, CA	7	3	Hot-Dry
Santa Clara, CA	4	3	Marine
Oakland, CA	3	3	Marine
Washington, D.C.	N/A	4A	Mixed-Humid
Seattle, WA	N/A	4C	Marine
Denver, CO	N/A	5B	Cold
Minneapolis, MN	N/A	6A	Cold
Fairbanks, AK	N/A	8	Very Cold

4.2 Prototype Buildings

Three prototype buildings were used to provide a variety of use cases that might be helpful for utilities with multiple residential building types in their building stocks. Table 6 shows the square footage, window U-factor, and insulation levels assumed for each of the prototypes.

4.3 Window Area

Window area usually is based on a percentage of window-to-wall area. The most common percentage of window-to-wall area is 15% (Wilson et al. 2014). This is also the same percentage of window-to-wall area in the PNNL Lab Homes. To capture a variety of window sizes, an additional parameter of 18% window-to-wall area was used to capture the potential energy savings for homes with especially large window areas.

Table 6. Prototype Characteristics

Prototype	Square Footage	Window U-Factor	Wall R-Value	Roof/Ceiling R-Value	Floor R-Value
Prototype #1 (New) ¹	2400	0.32	R-13 in IECC CZ 1-4B	R-30 in IECC CZ 1-3	R-13 in IECC CZ 1-2
			R-20/13+5 in IECC CZ 4C-6	R-38 in IECC CZ 4-5	R-19 in IECC CZ 3-4B
			R-21 in IECC CZ 7-8	R49 in IECC CZ 6-8	R30 in IECC CZ 4C-6; R-38 in IECC CZ 7-8
Prototype #2 (Existing)	2400	0.68	R-11	R-22	R-22
Prototype #3 (Existing)	1500	0.68	R-11	R-22	R-22

Note: Based on the current energy code adoption status, most states have adopted the 2009 edition of the IECC or an amended version with a stringency between the 2009 and the 2012 version of the IECC (<https://www.energycodes.gov/adoption/states>). Thus, the prototype is assumed to follow residential provisions of the 2009 edition of the IECC as it roughly represents a typical new home.

4.4 Window Types

Two types of windows were modeled for the parametric study. Details about the window types are provided in Section 3.1. For reference, the two window types used are described below:

- Window with a U-factor of 0.32 for new homes
- Window with a U-factor of 0.68 for existing homes.

The window U-factor was assumed to be the same in all climates for new homes based on field data from DOE's Residential Energy Field Study that indicates almost all windows in new homes meet or exceed a U-factor of 0.35 (Cohan et al. 2016).

4.5 Cellular Shade Performance Levels

Two types of cellular shades were modeled for the parametric study, including double-cell semi-transparent cellular shades¹⁰ and the triple-cell cellular shades. To provide some consistency with the experimental results, the Hunter Douglas version of these shades were chosen from the LBNL Window Library.

¹⁰ These are representative of commonly available shades and are the highest selling product for Hunter Douglas.

5.0 Results

Because of the simple schedule chosen for this study (see Section 3.2), results from the parametric study represent nearly best-case saving estimates. Results represent year-round savings and are presented according to climate zone, which gives utilities a quick way to find results that are the most applicable to their jurisdictions.

5.1 Climate Zone 1A (Miami, Florida)

Tables 7 and 8 provide information about HVAC and whole-house energy savings potential of cellular shades in climate zone 1A.

Table 7. Modeled HVAC Energy Use and Savings in Climate Zone 1A

Prototype	Window-to-Wall Area (%)	HVAC Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	7857.8	6620.8	6519.9	16%	17%
	18%	8140.9	6683.8	6560.2	18%	19%
Prototype #2 (U=0.68)	15%	10800.3	8116.9	7961.2	25%	26%
	18%	11504.4	8276.6	8083.1	28%	30%
Prototype #3 (U=0.68)	15%	6255.0	4948.8	4848.5	21%	22%
	18%	6672.6	5141.1	5017.9	23%	25%

Table 8. Modeled Whole-House Energy Use and Savings in Climate Zone 1A

Prototype	Window-to-Wall Area (%)	Total Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	19296.8	18059.8	17958.9	6%	7%
	18%	19579.9	18122.2	17998.6	7%	8%
Prototype #2 (U=0.68)	15%	22239.3	19554.5	19398.9	12%	13%
	18%	22943.3	19713.6	19520.0	14%	15%
Prototype #3 (U=0.68)	15%	12733.9	11427.7	11327.3	10%	11%
	18%	13151.6	11620.0	11496.8	12%	13%

5.2 Climate Zone 2A (Houston, Texas)

Tables 9 and 10 provide information about HVAC and whole-house energy savings potential of cellular shades in climate zone 2A.

Table 9. Modeled HVAC Energy Use and Savings in Climate Zone 2A

Prototype	Window-to-Wall Area (%)	HVAC Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	9421.9	8086.6	7960.7	14%	16%
	18%	9553.4	7985.2	7833.7	16%	18%
Prototype #2 (U=0.68)	15%	12285.8	9490.2	9354.1	23%	24%
	18%	12842.7	9537.9	9355.7	26%	27%
Prototype #3 (U=0.68)	15%	6588.0	5038.4	4945.8	24%	25%
	18%	6981.1	5157.4	5037.6	26%	28%

Table 10. Modeled Whole-House Energy Use and Savings in Climate Zone 2A

Prototype	Window-to-Wall Area (%)	Total Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	21352.8	20017.5	19891.6	6%	7%
	18%	21484.3	19916.0	19764.5	7%	8%
Prototype #2 (U=0.68)	15%	24216.4	21420.5	21284.5	12%	12%
	18%	24773.2	21468.0	21285.8	13%	14%
Prototype #3 (U=0.68)	15%	13130.5	11580.9	11488.3	12%	13%
	18%	13523.6	11699.5	11579.6	13%	14%

5.3 Climate Zone 2B (Imperial County Airport, California)

Tables 11 and 12 provide information about HVAC and whole-house energy savings potential of cellular shades in climate zone 2B.

Table 11. Modeled HVAC Energy Use and Savings in Climate Zone 2B

Prototype	Window-to-Wall Area (%)	HVAC Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	10697.2	8959.1	8798.9	16%	18%
	18%	11058.3	9010.3	8818.4	19%	20%
Prototype #2 (U=0.68)	15%	14846.3	11151.0	10878.9	25%	27%
	18%	15821.2	11423.9	11083.5	28%	30%
Prototype #3 (U=0.68)	15%	8506.2	6390.5	6234.6	25%	27%
	18%	9137.4	6621.2	6427.3	28%	30%

Table 12. Modeled Whole-House Energy Use and Savings in Climate Zone 2B

Prototype	Window-to-Wall Area (%)	Total Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	22275.1	20536.9	20376.8	8%	9%
	18%	22636.1	20588.0	20396.4	9%	10%
Prototype #2 (U=0.68)	15%	26424.3	22728.5	22456.4	14%	15%
	18%	27399.1	23001.4	22660.9	16%	17%
Prototype #3 (U=0.68)	15%	15003.3	12887.6	12731.6	14%	15%
	18%	15634.4	13118.2	12924.4	16%	17%

5.4 Climate Zone 3 (Sacramento Metro Airport, California)

Tables 13 and 14 provide information about HVAC and whole-house energy savings potential of cellular shades in climate zone 3.

Table 13. Modeled HVAC Energy Use and Savings in Climate Zone 3

Prototype	Window-to-Wall Area (%)	HVAC Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	10755.0	9322.7	9181.5	13%	15%
	18%	10857.5	9128.8	8955.6	16%	18%
Prototype #2 (U=0.68)	15%	14271.7	11067.2	10934.1	22%	23%
	18%	14902.3	11028.1	10840.8	26%	27%
Prototype #3 (U=0.68)	15%	7420.1	5451.1	5354.2	27%	28%
	18%	7891.4	5527.2	5397.8	30%	32%

Table 14. Modeled Whole-House Energy Use and Savings in Climate Zone 3

Prototype	Window-to-Wall Area (%)	Total Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	23209.9	21778.1	21636.8	6%	7%
	18%	23312.3	21583.9	21410.7	7%	8%
Prototype #2 (U=0.68)	15%	26725.7	23521.8	23388.7	12%	12%
	18%	27356.3	23482.4	23295.2	14%	15%
Prototype #3 (U=0.68)	15%	14031.0	12062.4	11965.5	14%	15%
	18%	14502.2	12138.5	12009.1	16%	17%

5.5 Climate Zone 3 (Burbank - Glendale, California)

Tables 15 and 16 provide information about HVAC and whole-house energy savings potential of cellular shades in climate zone 3.

Table 15. Modeled HVAC Energy Use and Savings in Climate Zone 3

Prototype	Window-to-Wall Area (%)	HVAC Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	7244.8	5894.8	5774.5	19%	20%
	18%	7484.6	5873.6	5727.5	22%	23%
Prototype #2 (U=0.68)	15%	10428.4	7478.1	7311.1	28%	30%
	18%	11149.9	7585.4	7364.5	32%	34%
Prototype #3 (U=0.68)	15%	6050.9	4362.6	4256.1	28%	30%
	18%	6549.8	4536.2	4399.1	31%	33%

Table 16. Modeled Whole-House Energy Use and Savings in Climate Zone 3

Prototype	Window-to-Wall Area (%)	Total Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	19470.4	18120.8	18000.6	7%	8%
	18%	19710.0	18099.4	17953.3	8%	9%
Prototype #2 (U=0.68)	15%	22653.7	19703.4	19536.4	13%	14%
	18%	23375.2	19810.0	19589.0	15%	16%
Prototype #3 (U=0.68)	15%	12632.0	10943.6	10837.1	13%	14%
	18%	13130.8	11117.2	10980.1	15%	16%

5.6 Climate Zone 3 (San Diego – Lindbergh, California)

Tables 17 and 18 provide information about HVAC and whole-house energy savings potential of cellular shades in climate zone 3.

Table 17. Modeled HVAC Energy Use and Savings in Climate Zone 3

Prototype	Window-to-Wall Area (%)	HVAC Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	4831.7	3693.4	3603.9	24%	25%
	18%	5099.9	3726.2	3612.8	27%	29%
Prototype #2 (U=0.68)	15%	7536.9	4900.0	4763.4	35%	37%
	18%	8223.2	4993.9	4817.2	39%	41%
Prototype #3 (U=0.68)	15%	4736.2	3320.2	3224.9	30%	32%
	18%	5191.5	3521.2	3401.0	32%	34%

Table 18. Modeled Whole-House Energy Use and Savings in Climate Zone 3

Prototype	Window-to-Wall Area (%)	Total Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	17070.5	15932.6	15843.0	7%	7%
	18%	17338.5	15964.7	15851.3	8%	9%
Prototype #2 (U=0.68)	15%	19775.6	17137.6	17000.8	13%	14%
	18%	20461.8	17230.2	17053.5	16%	17%
Prototype #3 (U=0.68)	15%	11318.5	9903.1	9807.3	13%	13%
	18%	11773.9	10104.1	9983.4	14%	15%

5.7 Climate Zone 3 (Santa Clara, California)

Tables 19 and 20 provide information about HVAC and whole-house energy savings potential of cellular shades in climate zone 3.

Table 19. Modeled HVAC Energy Use and Savings in Climate Zone 3

Prototype	Window-to-Wall Area (%)	HVAC Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	7750.2	6608.3	6502.9	15%	16%
	18%	7877.5	6473.3	6341.9	18%	19%
Prototype #2 (U=0.68)	15%	10809.8	8135.1	7998.2	25%	26%
	18%	11409.2	8127.6	7936.5	29%	30%
Prototype #3 (U=0.68)	15%	5965.3	4280.5	4172.2	28%	30%
	18%	6417.8	4399.2	4257.0	31%	34%

Table 20. Modeled Whole-House Energy Use and Savings in Climate Zone 3

Prototype	Window-to-Wall Area (%)	Total Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	20325.1	19183.9	19078.6	6%	6%
	18%	20452.3	19048.7	18917.5	7%	8%
Prototype #2 (U=0.68)	15%	23384.0	20709.9	20573.0	11%	12%
	18%	23983.2	20701.7	20510.7	14%	14%
Prototype #3 (U=0.68)	15%	12592.0	10907.7	10799.3	13%	14%
	18%	13044.4	11026.3	10884.1	15%	17%

5.8 Climate Zone 3 (Oakland, California)

Tables 21 and 22 provide information about the HVAC and whole-house energy savings potential of cellular shades in climate zone 3.

Table 21. Modeled HVAC Energy Use and Savings in Climate Zone 3

Prototype	Window-to-Wall Area (%)	HVAC Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	7695.0	6870.6	6795.4	11%	12%
	18%	7743.1	6666.9	6568.1	14%	15%
Prototype #2 (U=0.68)	15%	10428.4	7478.1	7311.1	28%	30%
	18%	11149.9	7585.4	7364.5	32%	34%
Prototype #3 (U=0.68)	15%	5572.8	4006.7	3900.9	28%	30%
	18%	5971.9	4098.5	3957.4	31%	34%

Table 22. Modeled Whole-House Energy Use and Savings in Climate Zone 3

Prototype	Window-to-Wall Area (%)	Total Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	20378.4	19555.4	19480.4	4%	4%
	18%	20426.3	19351.5	19252.9	5%	6%
Prototype #2 (U=0.68)	15%	22653.7	19703.4	19536.4	13%	14%
	18%	23375.2	19810.0	19589.0	15%	16%
Prototype #3 (U=0.68)	15%	12214.4	10649.2	10543.4	13%	14%
	18%	12613.5	10740.6	10599.4	15%	16%

5.9 Climate Zone 4A (Washington, D.C.)

Tables 23 and 24 provide information about the HVAC and -house energy savings potential of cellular shades in climate zone 4A.

Table 23. Modeled HVAC Energy Use and Savings in Climate Zone 4A

Prototype	Window-to-Wall Area (%)	HVAC Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	15957.3	14648.6	14486.1	8%	9%
	18%	15719.9	14161.6	13964.6	10%	11%
Prototype #2 (U=0.68)	15%	19371.3	16514.0	16461.8	15%	15%
	18%	19495.7	16082.5	15984.0	18%	18%
Prototype #3 (U=0.68)	15%	8999.4	7184.2	7119.3	20%	21%
	18%	9255.4	7097.0	6996.2	23%	24%

Table 24. Modeled Whole-House Energy Use and Savings in Climate Zone 4A

Prototype	Window-to-Wall Area (%)	Total Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	28792.9	27484.6	27322.1	5%	5%
	18%	28555.2	26997.2	26800.2	5%	6%
Prototype #2 (U=0.68)	15%	32206.3	29349.5	29297.3	9%	9%
	18%	32330.4	28917.7	28819.2	11%	11%
Prototype #3 (U=0.68)	15%	15657.9	13843.1	13778.3	12%	12%
	18%	15913.4	13755.5	13654.7	14%	14%

5.10 Climate Zone 4C (Seattle, Washington)

Tables 25 and 26 provide information about HVAC and whole-house energy savings potential of cellular shades in climate zone 4C.

Table 25. Modeled HVAC Energy Use and Savings in Climate Zone 4C

Prototype	Window-to-Wall Area (%)	HVAC Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	11270.3	10628.1	10532.8	6%	7%
	18%	11148.5	10274.3	10154.9	8%	9%
Prototype #2 (U=0.68)	15%	16667.0	14679.0	14695.4	12%	12%
	18%	16812.0	14273.7	14261.1	15%	15%
Prototype #3 (U=0.68)	15%	7752.2	6202.0	6182.0	20%	20%
	18%	7962.1	6059.2	6015.3	24%	24%

Table 26. Modeled Whole-House Energy Use and Savings in Climate Zone 4C

Prototype	Window-to-Wall Area (%)	Total Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	24272.1	23631.4	23536.3	3%	3%
	18%	24149.9	23277.5	23158.2	4%	4%
Prototype #2 (U=0.68)	15%	29668.4	27681.9	27698.4	7%	7%
	18%	29813.2	27276.5	27263.9	9%	9%
Prototype #3 (U=0.68)	15%	14434.9	12886.2	12866.1	11%	11%
	18%	14644.3	12743.4	12699.4	13%	13%

5.11 Climate Zone 5B (Denver, Colorado)

Tables 27 and 28 provide information about HVAC and-house energy savings potential of cellular shades in climate zone 5B.

Table 27. Modeled HVAC Energy Use and Savings in Climate Zone 5B

Prototype	Window-to-Wall Area (%)	HVAC Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	13656.9	12438.1	12282.7	9%	10%
	18%	13589.1	12103.6	11916.7	11%	12%
Prototype #2 (U=0.68)	15%	20213.4	17333.9	17181.7	14%	15%
	18%	20602.0	17084.1	16873.5	17%	18%
Prototype #3 (U=0.68)	15%	7751.6	6200.9	6182.4	20%	20%
	18%	7964.6	6057.5	6015.9	24%	24%

Table 28. Modeled Whole-House Energy Use and Savings in Climate Zone 5B

Prototype	Window-to-Wall Area (%)	Total Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	26704.2	25486.1	25330.8	5%	5%
	18%	26636.1	25151.3	24964.5	6%	6%
Prototype #2 (U=0.68)	15%	33260.6	30381.8	30229.6	9%	9%
	18%	33649.0	30131.5	29921.3	10%	11%
Prototype #3 (U=0.68)	15%	14439.5	12890.2	12871.7	11%	11%
	18%	14652.0	12746.4	12704.8	13%	13%

5.12 Climate Zone 6A (Minneapolis, Minnesota)

Tables 29 and 30 provide information about HVAC and whole-house energy savings potential of cellular shades in climate zone 6A.

Table 29. Modeled HVAC Energy Use and Savings in Climate Zone 6A

Prototype	Window-to-Wall Area (%)	HVAC Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	23679.4	22533.9	22352.6	5%	6%
	18%	23377.5	21963.0	21743.9	6%	7%
Prototype #2 (U=0.68)	15%	31646.3	28814.4	28800.5	9%	9%
	18%	31534.3	28050.2	27999.7	11%	11%
Prototype #3 (U=0.68)	15%	13966.2	11962.0	11920.6	14%	15%
	18%	14065.5	11639.0	11562.3	17%	18%

Table 30. Modeled Whole-House Energy Use and Savings in Climate Zone 6A

Prototype	Window-to-Wall Area (%)	Total Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	37095.7	35951.0	35769.7	3%	4%
	18%	36793.6	35380.0	35160.9	4%	4%
Prototype #2 (U=0.68)	15%	45062.5	42231.7	42217.7	6%	6%
	18%	44950.3	41467.2	41416.8	8%	8%
Prototype #3 (U=0.68)	15%	20698.3	18695.0	18653.6	10%	10%
	18%	20797.5	18371.5	18294.9	12%	12%

5.13 Climate Zone 8 (Fairbanks, Alaska)

Tables 31 and 32 provide information about HVAC and whole-house energy savings potential of cellular shades in climate zone 8.

Table 31. Modeled HVAC Energy Use and Savings in Climate Zone 8

Prototype	Window-to-Wall Area (%)	HVAC Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	39412.1	38809.7	38625.3	2%	2%
	18%	39127.5	38233.0	38003.7	2%	3%
Prototype #2 (U=0.68)	15%	52321.7	50114.3	50144.5	4%	4%
	18%	52237.7	49307.2	49316.0	6%	6%
Prototype #3 (U=0.68)	15%	23680.7	21777.6	21776.6	8%	8%
	18%	23768.4	21324.0	21303.2	10%	10%

Table 32. Modeled Whole-House Energy Use and Savings in Climate Zone 8

Prototype	Window-to-Wall Area (%)	Total Energy Use (kWh/yr) Based on Cellular Shade Performance Level			Percent Savings Compared to No Shades	
		No Shades	Double Cell	Triple Cell	% Savings of Double-Cell Shades	% Savings of Triple-Cell Shades
Prototype # 1 (U=0.32)	15%	53825.9	53225.2	53041.0	1%	1%
	18%	53541.0	52648.5	52419.3	2%	2%
Prototype #2 (U=0.68)	15%	66735.3	64529.9	64560.1	3%	3%
	18%	66651.0	63722.6	63731.5	4%	4%
Prototype #3 (U=0.68)	15%	30541.1	28639.9	28638.9	6%	6%
	18%	30628.4	28185.9	28165.1	8%	8%

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6.0 Conclusions

Overall, the parametric study showed a few trends:

- More energy savings can be realized in hot climates than in cold climates, although this may be attributable to the fact that cellular shades are operated optimally from an energy savings perspective during the cooling season (i.e., always pulled down), while the heating season operation is only partially optimized from an energy perspective.
- Triple-cell shades tend to save 0 to 2% more than double-cell shades for a given prototype. The colder the climate, the less the cellular shade performance level makes a difference.
- Well-insulated new homes with relatively high performing windows generally provide less energy savings potential than existing homes with the same square footage (comparing prototype #1 as a new home, to prototype #2 as an existing home with the same square footage).
- The more window area a home has, the more energy savings cellular shades can provide.
- Smaller existing homes tend to realize more energy savings than larger existing homes with the same house characteristics and window types (based on comparing results from prototype #2 at 2400 square feet and prototype #3 at 1500 square feet with no other differences).
- Energy savings (for triple-cell shades) associated with HVAC operation ranges from 3 to 29% for relatively large new homes with large window area, depending on climate zone.
- Energy savings (for triple-cell shades) associated with HVAC operation ranges from 10 to 34% for a relatively small existing home with a large window area, depending on climate zone.

In conclusion, based on the trends described above, cellular shades would provide the best energy savings potential in smaller existing homes, with relatively large window areas, in warmer climates. Double-cell cellular shades will provide nearly the same energy savings as triple-cell cellular shades.

For this study, the simulated saving results depend on specific shading schedules. It is not likely that an occupant would precisely follow these schedules manually; however, there are options for automating shading controls for more persistent savings. New and emerging integrating platforms also can optimize shade control based on weather conditions and occupancy status. Whether through automation or manual operation, utility programs could provide valuable information and incentives to help consumers realize energy savings from window attachments by both selecting and operating window attachments appropriate for their homes and climate zones.

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7.0 References

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