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Energy Performance of Awnings in Residential Buildings

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Buildings and Transportation Science Division

ENERGY PERFORMANCE OF AWNINGS IN RESIDENTIAL BUILDINGS

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September 2022

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ABSTRACT

Residential buildings consume approximately 20% of the total primary energy in the United States. More than 50% of this energy is spent in heating, cooling, and lighting these buildings. Solar heat gain is one of the largest and most variable sources of cooling load in these buildings, while it can also provide passive heating during the heating season. Shading devices can be used to control the amount of solar heat gain in buildings. Various studies have considered how different shading devices and their applications affect energy and occupant comfort in buildings. However, most of these studies were limited to planar shading devices such as roller shades, cellular shades, and blinds. Although some theoretical studies have been performed for awnings, the energy performance of awnings has rarely been studied via either energy simulation or field measurement. In this study, the authors evaluated the energy performance of typical operable awnings by using field data, aided by simulation. Awnings were installed on a real house, and measurements were performed to evaluate the thermal performance of the awning. The measured data were then used to develop a calibrated energy model and evaluate the awning's energy performance. The annual simulation of the building model used showed that awnings left in the closed position from April to September can reduce annual HVAC energy consumption by 15% compared with a building without any shades. The validated model was used in US Department of Energy prototype buildings to evaluate awning energy performance in climate zones 1A through 4B via energy simulation. For these prototype buildings, energy savings of up to 1,034 kWh were achieved for a building with a conditioned floor area of 2,377 ft^2.

1. OBJECTIVE

The overall objective of this project was to evaluate the typical use of operable awnings and validate the energy performance of awning products. Awnings were installed on a real house, and measurements were performed to evaluate the thermal performance of these awnings at different positions. The measured data were used to develop a calibrated energy model to estimate the annual energy savings.

2. BENEFITS TO THE FUNDING DOE OFFICE'S MISSION

The mission of the US Department of Energy's (DOE's) Building Technologies Office (BTO) Emerging Technologies (ET) Program is to develop technologies that can facilitate meeting the BTO's strategic goal of reducing US building energy use per square foot by 30% by 2030 vs. the 2010 baseline. Per the BTO's report (U.S. Department of Energy 2014), the 2030 technical potential of window attachments is 991 TBtu. Pacific Northwest National Laboratory conducted a study that estimated that installing a high-efficiency window attachment could reduce heating and cooling consumption by an average of 5%–30% in residential single- and multi-family homes and small commercial buildings. The project discussed in this report will contribute to achieving the BTO's 2030 strategic goal. The successful outcome of this project will help the Attachment Energy Rating Council (AERC) expedite the rating program for awning products so that awnings can be considered for inclusion in the EnergyStar program.

3. TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES

Residential buildings consume approximately 20% of the total primary energy in the United States (US EIA 2019). More than 50% of this energy is spent in heating, cooling, and lighting these buildings. Solar heat gain is one of the largest and most variable sources of cooling load in these buildings, and it can also provide passive heating during the heating season. Shading devices can be used to control the amount of solar heat gain in buildings. Various studies have considered how different shading devices and their applications affect energy and occupant comfort in buildings. However, many of these studies were based on simulation, and few performed experimental testing in laboratory settings (Kunwar, Cetin, and Passe 2018). Most studies focused on shading devices, such as planar shades (Kunwar et al. 2019) and blinds (Kunwar et al. 2020; Konstantoglou and Tsangrassoulis 2016). Although some theoretical studies have been performed for awnings (Gómez-Muñoz and Porta-Gándara 2003), the energy performance of awnings has rarely been studied via either energy simulation or field measurement.

Awnings can provide visual comfort, significantly reduce cooling load, and provide overall energy savings in residential buildings. Several studies have shown that using exterior window shading devices improves thermal and visual comfort in residential and commercial buildings (Sites and Cort 2020; Hoffmann and Lee 2015). The solar-control performance of awnings depends on the fabric's material properties, such as solar transmittance and absorptance (Kuhn 2017), and on the awning's position. One main advantage of using awnings instead of planar shades is that awnings block solar irradiation without obstructing occupants' view of the outdoors. Evaluating awning performance will help AERC expedite the rating program for awning products. Field validation in residential buildings can help evaluate various standard AERC operating schedules (e.g., fixed, seasonal fixed, operable) and prepare guidelines for future automated operation schedules. As AERC continues the product ratings, there is a need for more field and case studies to prove or highlight the benefits of these products in residential buildings. In addition to energy savings, awning systems could:

- reduce the HVAC size in existing houses or the peak load in new houses,
- provide daylighting (i.e., a system that provides natural light, reducing the artificial lighting needs of the building) and a control system that would ensure proper daylighting without glare,
- improve occupant thermal and visual comfort, and
- be easily installed without greatly disrupting the occupant.

Awnings were installed on a real house, and measurements were taken to evaluate the awning's thermal performance and potential effect on occupant comfort. The measured data were then used to validate the awning model for its energy performance. The validated model was used in DOE prototype buildings to evaluate awning energy performance in ASHRAE climate zones 1A through 4B via energy simulation. Section 3.1 describes the retractable awnings, Section 3.2 describes the experimental testing, Section 3.3 discusses the model creation and validation, and Section 3.4 discusses the annual energy simulation via the prototype buildings.

3.1 AWNING TECHNOLOGY DESCRIPTION

Awnings are exterior window shades that block solar radiation before it reaches the window. Thus, awnings protects windows from heat, glare, and ultraviolet rays, and they can reduce solar heat gain more effectively than interior shades (LBNL n.d.). Awnings can improve building thermal performance by reducing solar heat gain when cooling is needed and increasing solar heat gain when heating is needed. Awnings can be controlled or configured to optimize shading performance throughout the year based on the location of the house or orientation of the facade where the awnings are installed.

Drop-arm awnings are operable roller shades that can be fully retracted or deployed at different angles and different lengths. The awning position is changed by moving the hinged arms, which are typically located halfway down the window (Curcija et al. 2013). A sketch of a drop-arm awning is provided in Figure 1. These awnings can be adjusted to different positions and thus provide a flexible amount of shade. A motor located inside the housing controls the awning position and can retract or deploy the shade to different positions. When retracted, the fabric rolls up inside the housing. These motors can be hard wired, or battery powered with optional features like solar panel to charge the battery. The motor can be controlled wirelessly via smart phone applications and use feedback from weather data accessed by such applications. Some awnings are also equipped with rain and/or wind sensors. These sensors retract the awnings when there is high wind or rain and protect the awnings from weather damage. Awnings can also be integrated with a building automation system or home energy management system.

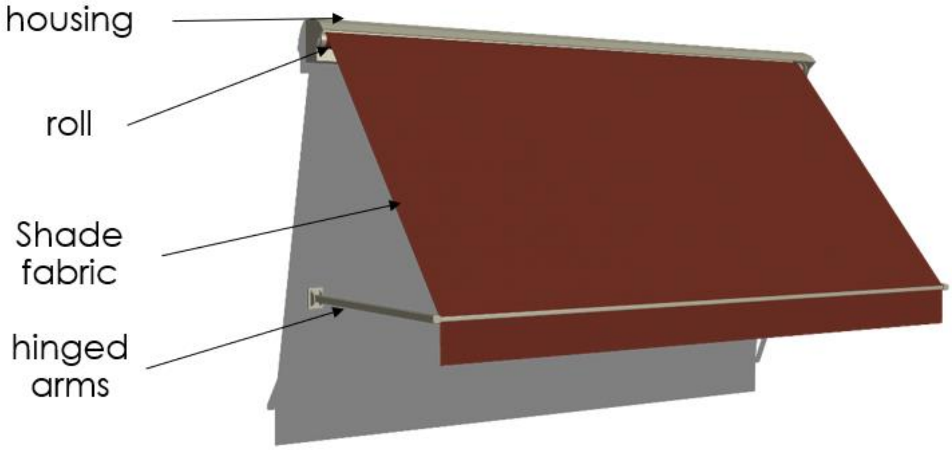

Figure 1. A sketch of a drop-arm awning system.

3.2 EXPERIMENTAL TESTING

The authors performed experimental tests over approximately 4 months in a residential house located in Atlanta, Georgia. This location was chosen because it is located in ASHRAE climate zone 3A (i.e., warm-humid region) and requires significant cooling during the summer. The house also had many windows on its southern facade, as shown in Figure 2. The house was built in the early 2000s and was equipped with two different air-conditioning systems: one for the first floor and one for the second floor. The basement was unconditioned.

Figure 2. House in Atlanta, Georgia, where the awnings were installed.

3.2.1 Sensors and Instruments

Different sensors and instruments were used to monitor energy consumption, air temperature, window surface temperature, solar irradiation, and daylighting conditions. Most sensors—such as window surface temperature, solar irradiation, and daylighting sensors—were installed in only one of the rooms because the other windows on the same facade were assumed to have characteristics similar to the window from which the measurement was taken. However, this assumption might not always be correct if exterior objects shade some part of the facade. Table 1 lists the sensors used during the experiment.

Table 1. Sensors and instruments used during the experiment.

Measurement	Device	No.	Placement
HVAC energy consumption	Sub-metering device	2	
Ambient temperature/Relative Humidity (RH)	Air temperature and RH sensor	2	One inside, one outside
Solar irradiation	Pyranometer	2	One inside, one outside
Ambient temperature/RH (HOBO)	Air temperature and RH sensor	2	One on each floor
Window surface temperature	Thermistors	4	Two inside, two outside
Mean radiant temperature	Globe temperature sensor	1	2 ft from the window at 3.28 ft height
Heat flux	Heat flux sensor	1	Interior surface of the window

The placement of various different sensors used during the experiment—including indoor pyranometers, thermistors, and heat flux sensors—are shown in Figure 3.

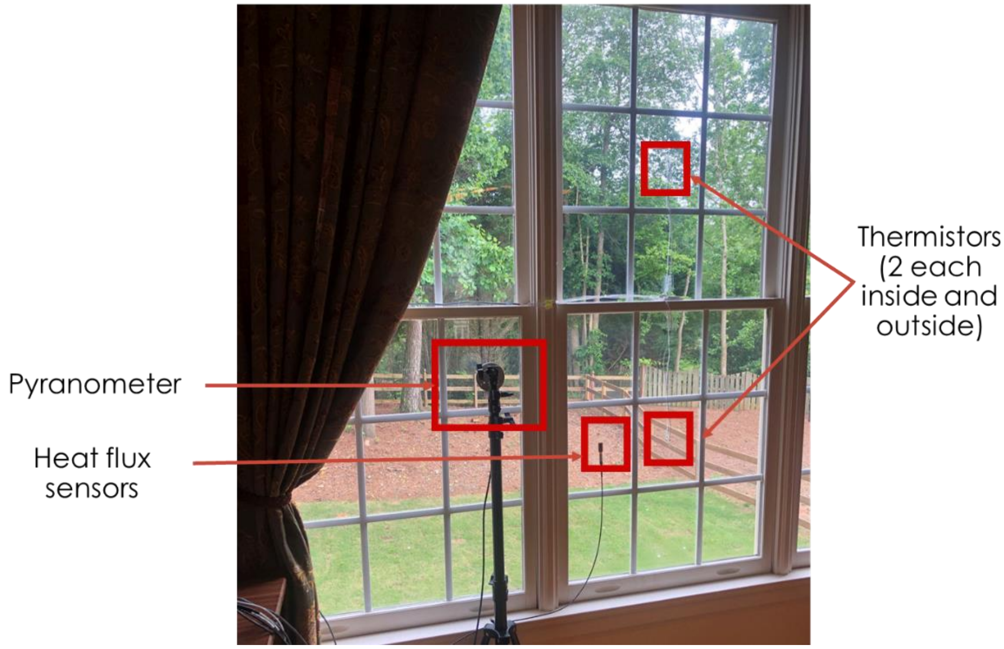

Figure 3. Placement of various sensors installed on one window.

A pyranometer was also installed on the exterior of the facade to monitor the solar irradiation hitting the facade. The position of the sensor shown in Figure 4 was chosen so that there was minimal probability of shading from external objects, such as trees or awnings.

Figure 4. Location of exterior pyranometer.

Interior illuminance sensors were placed 3.3 ft from the window, as shown in Figure 5. One vertical illuminance (VI) sensor at a height of 3.9 ft and one horizontal illuminance (HI) sensor at a height of 2.6 ft were used to observe how the awnings affected the daylighting level near the sensor position.

Figure 5. Illuminance sensors on the building interior.

3.2.2 Shading Device and AERC Rating

Drop-arm awnings from Glen Raven were used as the shading device. The fabric of the shading device (Sunbrella awning fabric FF-4676-0000) had a solar transmittance of 0.3% and a solar reflectance of 17.1%. We also performed the calculation for AERC rating of the awning fabric which is discussed in following paragraphs.

The AERC is an independent, public interest, non-profit organization whose mission is to rate, label, and certify the performance of window attachments. AERC will serve the public interest by providing accurate and credible information about the energy performance of window attachments, which will help consumers, including homeowners, architects, and builders, make informed decisions about window attachment products.

WINDOW (LBNL n.d.) and AERCalc program from LBNL were used to calculate the energy performance rating of the awnings. In WINDOW, typically SHGC and visible transmittance (VT) calculated at normal incidence do not account for attachments mounted above existing fenestration and projecting out from the plane of the existing fenestration to provide shading, such as awnings, which are sensitive to the actual solar angle and building geometry. Hence, alternative metrics of $SHGC_{Annual}$ and VT_{Annual} are used in the WINDOW to convey the optical properties of awning systems when placed on windows. $SHGC_{Annual}$ and VT_{Annual} are based on an average over multiple angles of incidence, derived from the set of solar angles developed for tubular daylighting devices (McCluney and Dupont 2010; Goudey et al. 2012). The AERC Annual Energy Rating is based on the application of these properties within AERCalc (LBNL 2018) for a model climate, a device operating schedule, and a factor for user engagement. The ratings are called the Energy Performance Cool Climate Rating (EPc) and the Energy Performance Warm Climate Rating (EPh). EPc, and EPh are defined as the ratio of annual cooling/heating energy saving resulting from the addition of window attachment to the annual energy use caused by the baseline window without attachment. EPc uses Houston, Texas as the model cooling climate, and EPh uses Minneapolis, Minnesota as the model heating climate.

Awnings are targeted to provide relief from unwanted solar heat. The EPc ratings for the Drop Arm awnings in this study are shown in the table below. The two positions – full deployment and midpoint deployment are each shown. The material of the fabric used for experimental testing was used in this AERCalc calculation. Three schedules may be used in modelling the impact of solar shading use in Houston:

1. Fixed – awning is deployed every hour of the year

2. Seasonal – awning is deployed every hour from April 15 to October 15

3. Operable – this is a complex set of parameters that show a range of shade use by a large population, which assumes that different portions of a population will (a) never deploy the shade, (b) adjust the shade for the weather, or (c) always leave the shade in a preferred position. This schedule is not optimized for any season or any condition. It serves as a conservative comparative rating with the AERC system, and is described in AERC 2 technical document (AERC 2017)

Schedule	Device and position or operation	$SHGC_{annual}$	VT_{annual}	EPc
Fixed	drop arm at full deployment	0.08	0.04	85
Fixed	drop arm at midpoint	0.20	0.18	52
Seasonal	drop arm at full deployment	0.08	0.04	61
Seasonal	drop arm at midpoint	0.20	0.18	35
AERC manual schedule	Operating drop arm. Partial population use, non-optimized. A combination of full, mid, and no deployment.			38

3.2.3 Shading Control and Test Cases

The test required that the awnings systems are controlled automatically for the defined fixed, seasonal and operable schedules. Somfy smart shading system was used to control the awnings in three different positions. Somfy, is a world leader in the manufacturing of specialized motors and electronic controls for residential and commercial interior and exterior window covering markets. Somfy had various options available for automation designed for residential as well as commercial interior attachments including interior shades, blinds, draperies, rolling shutters, awnings and more. For more information visit www.somfysystems.com. While some of these systems had the capability to be integrated with security, HVAC and lighting systems, a standalone control system from Somfy was selected for this project as the experimental home was not equipped with a home automation system.

The Tahoma application from Somfy (Somfy, n.d.) was used to control the awnings remotely by presetting the desired positions of the awnings during the initial shading control system setup. The application allowed creation of different scenes and schedules for controlling the awnings. The awnings were controlled as a group so that they were all either open, closed, or half-closed simultaneously. These different positions are described as follows.

- Open: No shade is provided; the awning is fully retracted.
- Closed: The drop-arm is at a 90° angle to the window with the valance hanging below that point.
- Half-closed: The lowest part of shade is at the window midpoint height.

The closed and half-closed awning positions for one of the windows are shown in Figure 6.

Figure 6. Closed and half-closed awning positions

The awnings were constantly set at one of the three positions during the entire test duration for each of the three cases. One test period typically spanned 7–10 days of testing, with two test periods of testing for each of the three positions. Six awnings were added in the south-facing windows of the house, as shown in Figure 7.

Figure 7. House after the installation of six awnings.

The effect of the awnings during the experiment was analyzed for variables such as solar irradiation transmission, illuminance at illuminance sensors, and house energy consumption.

3.2.3.1 Solar irradiation transmission

Solar heat gain is one of the major causes of cooling energy demand in residential buildings, and awnings can help reduce solar heat gain in buildings. The outdoor and transmitted solar irradiation for different test cases is shown in Figure 8, which indicates that the case with awnings had very low transmitted solar irradiation compared with the baseline case, despite having similar amounts of outdoor solar irradiation. When awnings were in the closed position, the average transmitted solar irradiation was around 12 W/m^2. The average transmitted solar irradiation was approximately 41 W/m^2 for the baseline case, which was more than three times the average transmitted solar irradiation for the closed position. Thus, awnings significantly reduced the solar heat gain in the house.

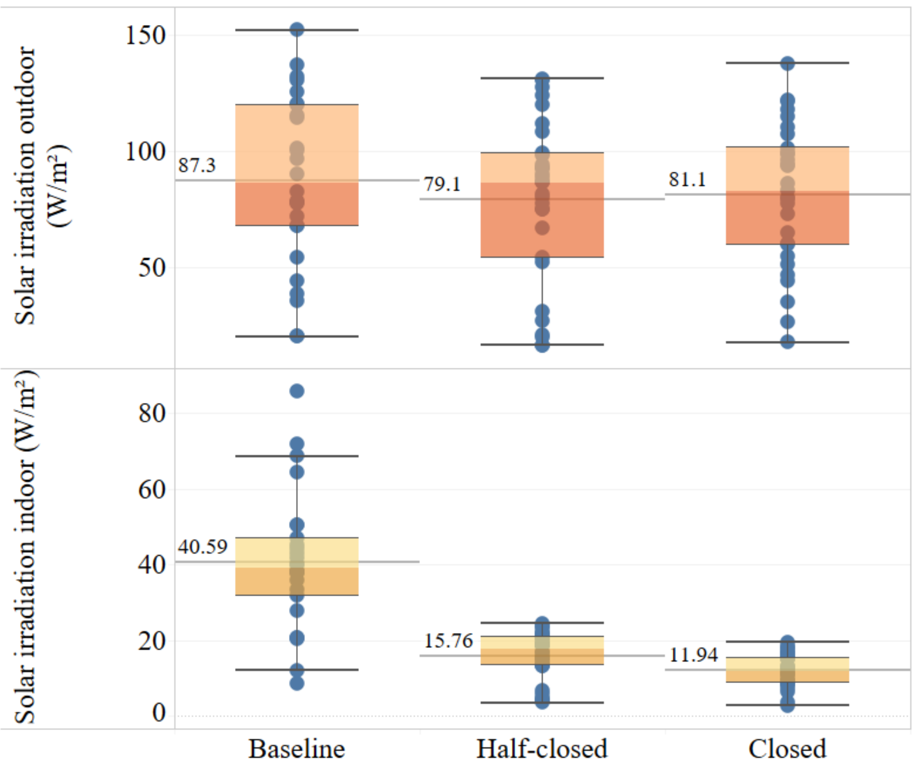

Figure 8. Distribution of daily average (data from 8:00 a.m. to 7:00 p.m.) of outdoor and transmitted solar irradiation for different cases.

3.2.3.2 Illuminance results

Awnings also help reduce excessive illuminance in buildings. Illuminance greater than 2,000 lux can cause visual discomfort to occupants (Nabil and Mardaljevic 2006; Wienold 2009). The results for average Vertical Illuminance (VI) and Horizontal Illuminance (HI) at 3.3 ft from the window for different test cases from this experiment are shown in Figure 9. Average HI and VI for baseline reach 5,000 and 3,500 lux respectively, during the afternoon. Awnings significantly reduce the average VI and HI in both the half-closed and closed positions keeping them lower than 2500 lux throughout the day, which prevents or mitigates visual discomfort from excessive daylighting.

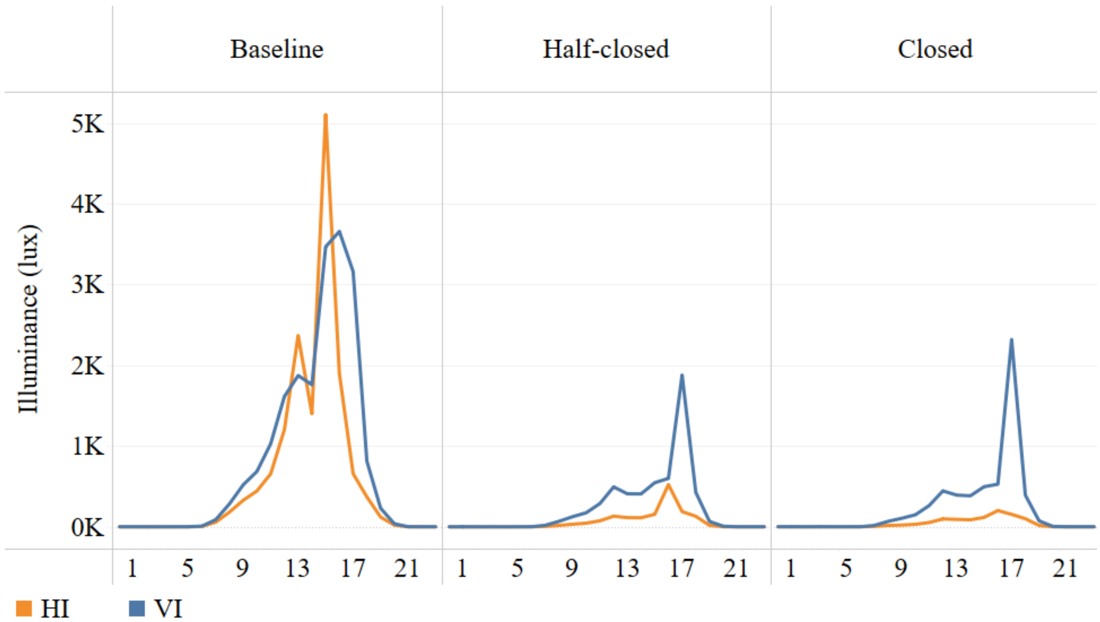

Figure 9. Average VI and HI for different test cases at each hour of the day.

3.2.3.3 Energy consumption

Figure 10 shows the daily energy consumption for the different cases along with the average outdoor temperature for the testing period. The energy consumption is shown as a box plot distribution together with box plot distribution of outdoor air temperature. The average daily energy consumption was higher for the baseline (29.02 kWh) than for the half-closed (25.79 kWh) and closed (24.56 kWh) cases. However, the mean outdoor temperature was also higher during the period when baseline testing was performed. Also, the distribution of daily HVAC energy consumption had a pattern similar to the distribution of average daily temperature, as shown in Figure 10. The linear regression between the HVAC energy consumption and mean outdoor temperature had an R-squared coefficient of 0.77. Furthermore, the effect of solar shading on an occupied building is difficult to evaluate accurately because of other factors, such as varying occupancy schedules, internal loads, and weather conditions, which make apple-to-apple comparisons difficult. Hence, the measured data were used to create a calibrated energy model, as discussed in the next section, to estimate the potential energy savings.

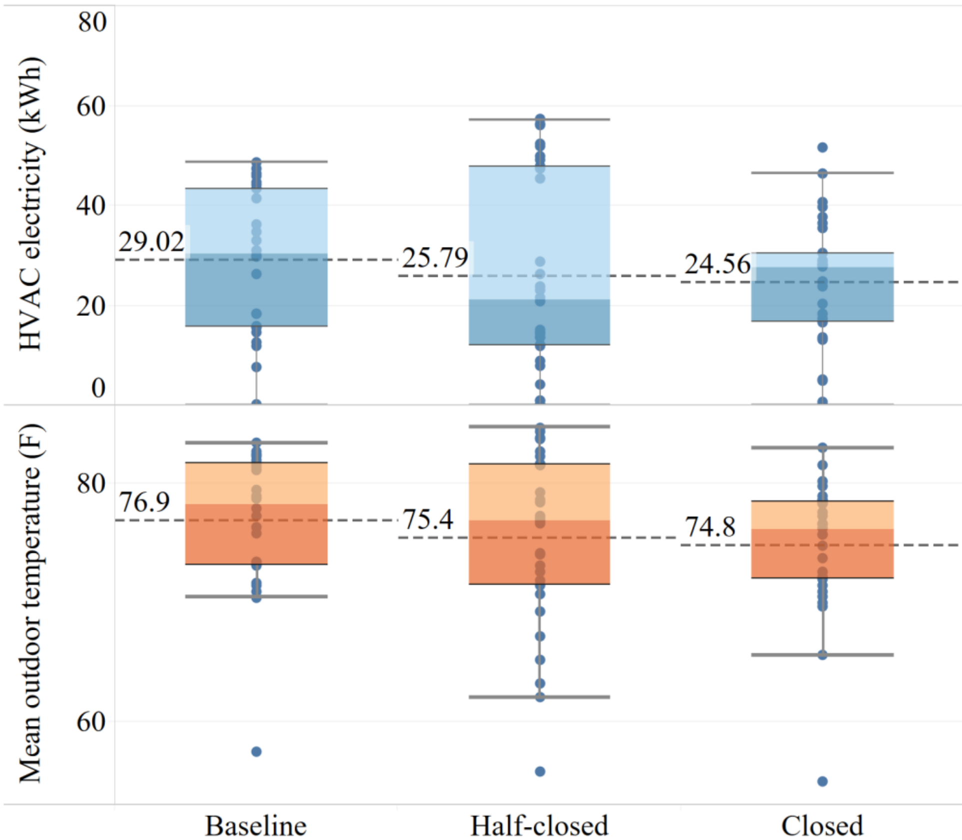

Figure 10. Box plot of daily energy consumption and corresponding outdoor temperature for three cases.

3.3 MODEL CALIBRATION AND ANNUAL SIMULATION

An energy model of the building was created by using the validated energy simulation software EnergyPlus (US Departament of Energy 2020). The model created in EnergyPlus was calibrated against the measured data by using the collected data and typical building characteristics for buildings of that age and location.

3.3.1 Building

The geometry of the energy model (Figure 11) was created by using the OpenStudio SketchUp plugin ("OpenStudio," n.d.). The information required for geometry was based on some of the measurements taken on-site and information provided by the homeowner. The material properties for the building's opaque envelope were based on the material properties of the envelope present in the International Energy Code Council (IECC) 2006 prototype residential building model for climate zone 3A. Two HVAC systems were modeled for the building to condition the first and second floors following the space-conditioning used for the actual house.

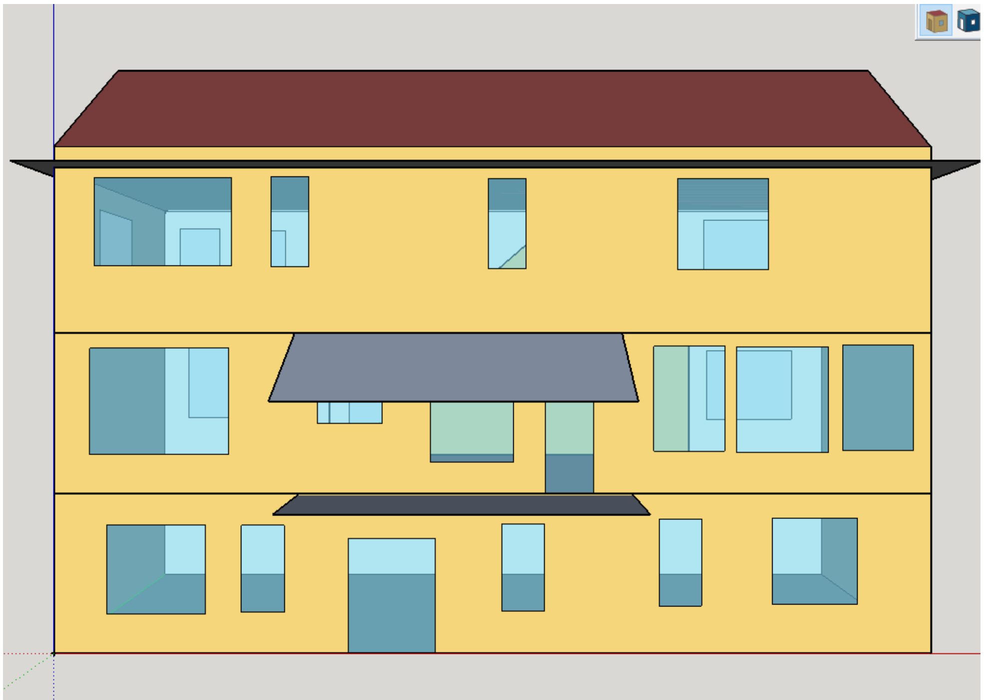

Figure 11. Geometry of the energy model (south facade).

3.3.2 Internal Load

The building internal load was modified from the internal load in the IECC 2006 prototype building based on the measured electricity consumption. The internal load in the model was made similar to the measured internal load. The measured internal load was assumed to be the difference between the total electricity and HVAC electricity consumption measurement of the house. This was done by creating a schedule by scaling the 0 to 99.5 percentile of the calculated internal load to a fraction ranging from 0 to 1. Figure 12 shows that the simulated and measured internal load were very similar to each other after tuning the internal load in the model to make it similar to measured internal load.

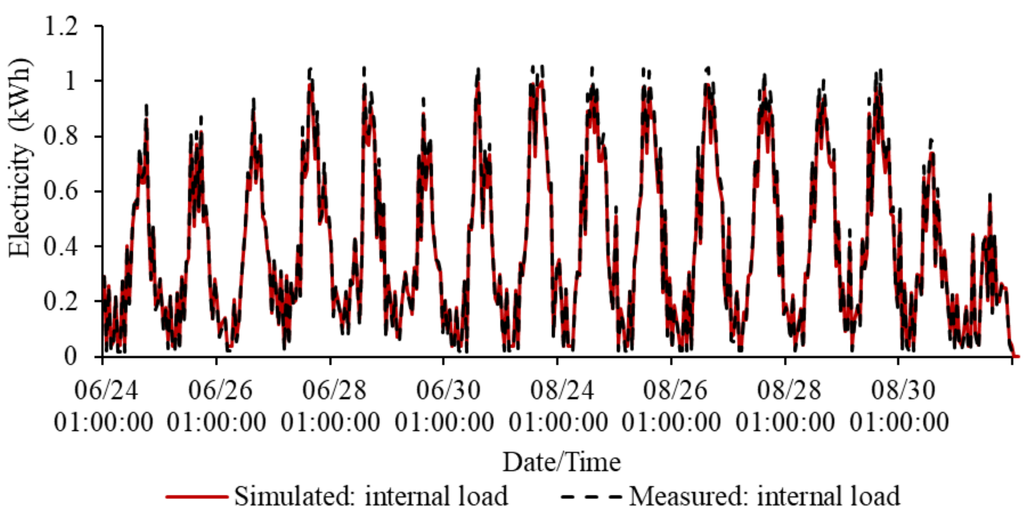

Figure 12. Measured and simulated internal load for the test house.

3.3.3 Shading Devices

Awnings with the FF-4676-0000 fabric were modeled for the half-closed and closed positions in WINDOW, but no shading devices were used for the baseline case. The fabric length and the angle of the fabric in relation to the window were calculated based on the window height and awning arm length of the installed awnings. Figure 6 shows the actual awning length and angle while in the closed and half-closed position for one window. The shading device modeled in WINDOW with a specified length and awning angle was then exported as a complex fenestration system (CFS) together with the window layers. This CFS or bidirectional scattering distribution function (BSDF) representation was used in EnergyPlus as the window construction for the energy simulation.

3.3.4 Results

Two metrics recommended by ASHRAE Guideline 14 (American Society of Heating Refrigeration and Air-Conditioning Engineers and ASHRAE 2014)—mean bias error (MBE) and coefficient of variation of the root-mean-square error (CV-RMSE)—were used to evaluate the model calibration. The MBE and CV-RMSE are defined as follows:

$$MBE = \frac{\sum_{i=1}^{n}(m_i - s_i)}{\sum_{i=1}^{n} m_i} * 10, \tag{1}$$

$$CV - RMSE = 100 * \left(\sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{(n-1)}}\right) * \frac{n}{\sum_{i=1}^{n} m_i}, \tag{2}$$

where m_i and s_i are the i^{th} measured and simulated data, respectively, and n is number of data points.

For the baseline case, the MBE between the measured and simulated data was 1.4%, and the CV-RMSE was 33.6%. The comparison of measured and simulated electricity for HVAV energy for the baseline case is shown in Figure 13. The simulated electricity consumption closely followed the measured electricity consumption.

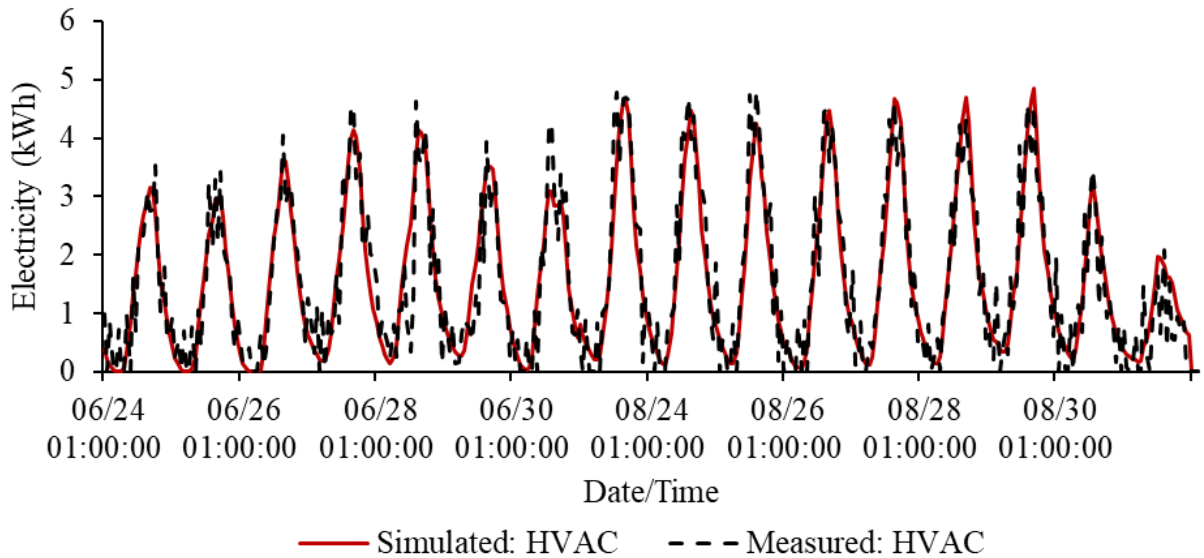

Figure 13. Measured and simulated HVAC consumption for the baseline case.

After calibrating the model for the baseline case, the awnings modeled in the half-closed and closed positions were added to represent the respective cases. The MBE and CV-RMSE were 9.5% and 50.6%, respectively, for the half-closed position and 15% and 47%, respectively, for the closed position.

Once the model calibration was complete, annual simulations were run for all three cases. However, the awnings were in the closed or half-closed position from April to September, which is assumed to be the cooling period. The HVAC electricity savings were 15.3% in the closed position and 12.1% in the half-closed position from April to September. The monthly electricity consumption for all three cases from April to September is shown in Figure 14. The energy savings during shoulder months, such as April and September, are similar to or higher than the energy savings during peak summer months, such as June, July, and August. This is because the solar radiation reaches the south facade at a lower angle during the shoulder months than in the summer months. Thus, the awnings prevented higher amounts of solar heat gain during the shoulder months than in peak summer months.

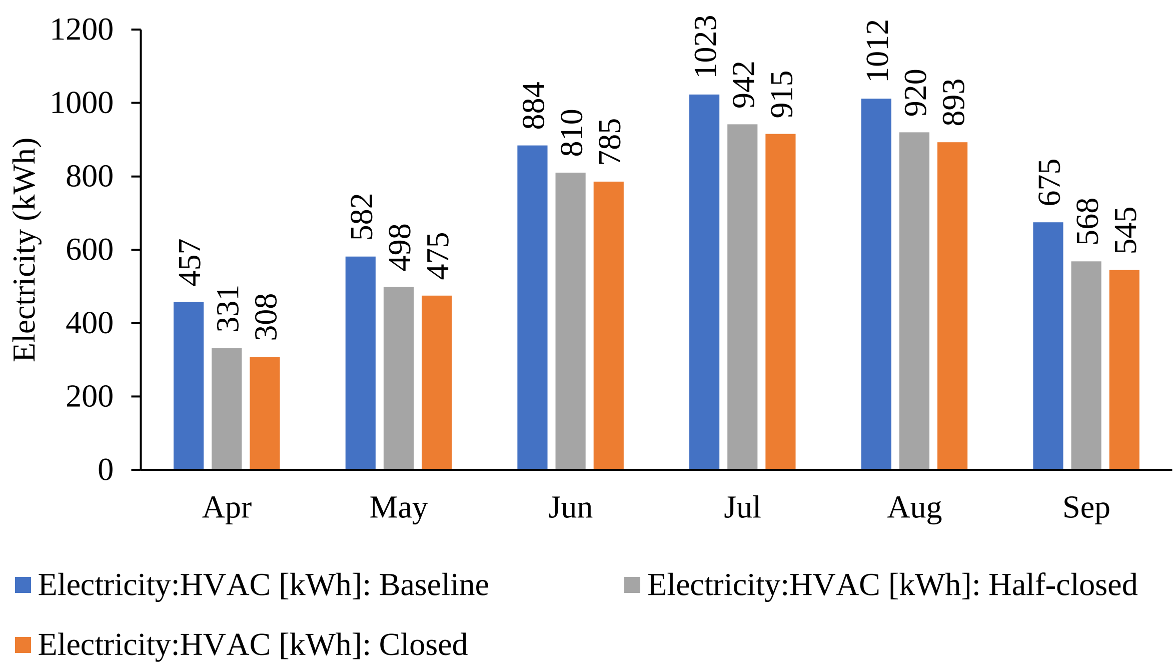

Figure 14. Monthly HVAC electricity from the test house model simulation for April through September.

3.4 PROTOTYPE BUILDINGS SIMULATION

DOE prototype buildings (PNNL n.d.) were used to evaluate the energy-saving potential of the awnings in climate zones 1A through 4B. The IECC 2018 model was used for the simulation. Residential prototype buildings with a heat pump heating system and slab foundation were used for the simulation. The building had a net conditioned floor area of 2,377 ft^2 and a total window area of approximately 355 ft^2.The simulation was performed for the baseline, half-closed, and closed awning positions from April 1 to September 30. This period was chosen because it was assumed to be the cooling season, and awnings are used only during the cooling season. Because the prototype building uses one U-value and solar heat gain coefficient (SHGC) window definition, which is unsuitable for the BSDF definition, a glazing with a similar U-value and SHGC was created in WINDOW. The representative city and properties of window glazing for different climate zones are provided in Table 2.

Table 2. Representative city and properties of window glazing at different climate zones.

Climate zone	Climate description	City, State	U-value (W/m^2-K)	SHGC
1A	Very hot-humid	Miami, Florida	2.157	0.201
2A	Hot-humid	Tampa, Florida	2.148	0.238
2B	Hot-dry	Tucson, Arizona	2.148	0.238
3A	Warm-humid	Atlanta, Georgia	2.148	0.238
3B	Warm-dry	El Paso, Texas	2.148	0.238
3C	Warm-marine	San Diego, California	2.148	0.238
4A	Mixed-humid	New York, New York	1.834	0.309
4B	Mixed-dry	Albuquerque, New Mexico	1.834	0.309

3.4.1 Results

The results for HVAC system energy consumption are shown in Figure 15, which includes combined energy consumption for heating and cooling applications. In the figure, the bar chart represents the energy consumption for different test cases, and the label in the bar chart is the difference of the baseline energy consumption and the test cases (i.e., a negative number represents the decrease in energy consumption compared with the baseline case). There is significant HVAC energy consumption for all the climate zones under consideration. For most climate zones, the heating energy penalty was negligible because the period from April to September is used for simulation; thus, the HVAC energy savings are similar to the energy savings from cooling applications. The energy consumption from April to September for heating and cooling is provided in Appendix A. This operation of awnings to be closed only from April to September helps avoid blocking solar heat gain during winter and the resulting heating energy penalty. The annual savings for HVAC energy were in the range of 454 to1,034 kWh. The energy savings from the awnings were highest in climate zone 2B. Surprisingly, the energy savings in climate zone 4B were higher than in zones 1A or 2A. The reason for this could be the higher amount of solar irradiation on climate zone 4B compared to 1A or 2A (NREL n.d.). Another reason might be the glazing in zone 4B had high SHGC compared with the glazing in zone 1A, as shown in Table 2. The shading device saved more energy when closed than when half closed; however, the half-closed position always provided more than 80% of the savings provided by the closed position.

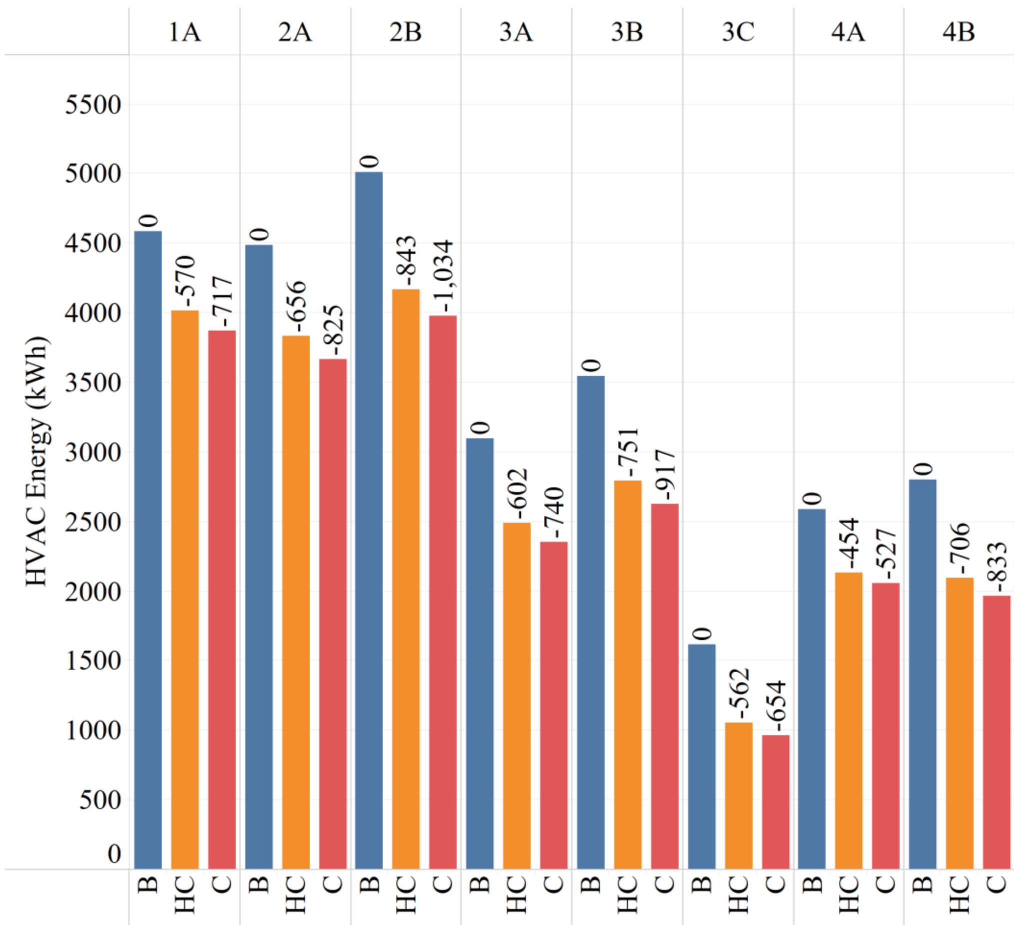

Figure 15. HVAC energy consumption for prototype buildings at six different climate locations for eight different cases. (B = baseline; C = closed; HC = half closed).

4. CONCLUSIONS

This study conducted experimental testing and simulations of awnings at two different positions to evaluate the energy performance of exterior awnings. Awnings achieved energy savings and reduced the solar heat gain during experimental testing. However, uncertainty was involved in the experimental testing due to variations in outdoor weather. In climate zone 3A, simulations of the same building used for experimental testing resulted in 15% energy savings with the awning in the closed position from April to September. Annual simulations were also performed for IECC DOE residential prototype buildings in which energy savings from awnings ranged from 454 to 1,034 kWh. The energy savings in mixed climate zone 4B were higher than in zones 1A and 1B, suggesting that awnings are beneficial not only in hotter climates but also in locations with a mixed climate. The awnings used in this study were set to a simple schedule to keep them in the half-closed or closed position during the cooling season. One advantage of using awnings instead of planar shades is that awnings can shade the whole window area without obstructing occupants' view of the outdoors.

One limitation of the study was that the awning schedule was fixed throughout the cooling season, which might not always be the case in a real-world situation. In a real-world situation, building occupants might manually intervene with the schedule to achieve daylighting, visual comfort, or a better view of the outside. Future work related to this study could involve controlling the awnings based on different input from buildings, such as outdoor or indoor temperature, solar irradiation in the facades on which awnings are installed, heating and cooling building requirements, and occupancy information. The automation of awnings based on these different variables can improve the energy savings potential of the solar awnings.

5. ACKNOWLEDGEMENT

We would like to thank Brett and Tammy Baird for providing their home awning installation and Brett for providing the guidance and support throughout the project. We would also like to thank Daniel Niemirka and Glen Sanders (Somfy) for providing the shade control systems and guidance during the different stages of the project. We would like to thank Marc LaFrance at the US Department of Energy for guiding this research.

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APPENDIX A. HEATING AND COOLING ENERGY CONSUMPTION FOR RESIDENTIAL PROTOTYPE BUILDINGS

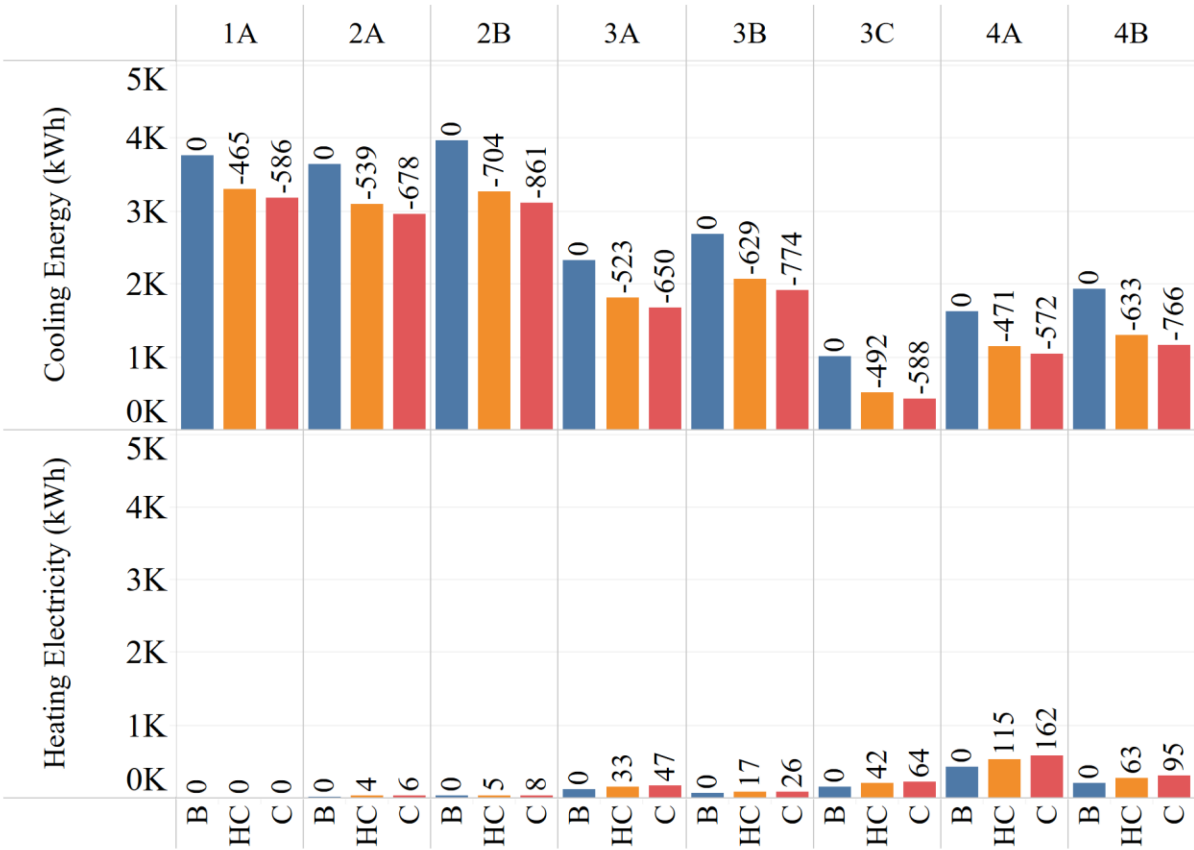

Figure A.1. Heating and cooling energy consumption for residential prototype buildings