Lawrence Berkeley National Laboratory
LBL Publications

Title
Non-Metalized Exterior Sun Control Film

Permalink
https://escholarship.org/uc/item/8mz212b1

Authors
Fernandes, Luis
Thanachareonkit, Anothai
Wang, Taoning
et al.

Publication Date
2026-10-12

Copyright Information
This work is made available under the terms of a Creative Commons Attribution License, available at https://creativecommons.org/licenses/by/4.0/

eScholarship.org Powered by the California Digital Library
University of California

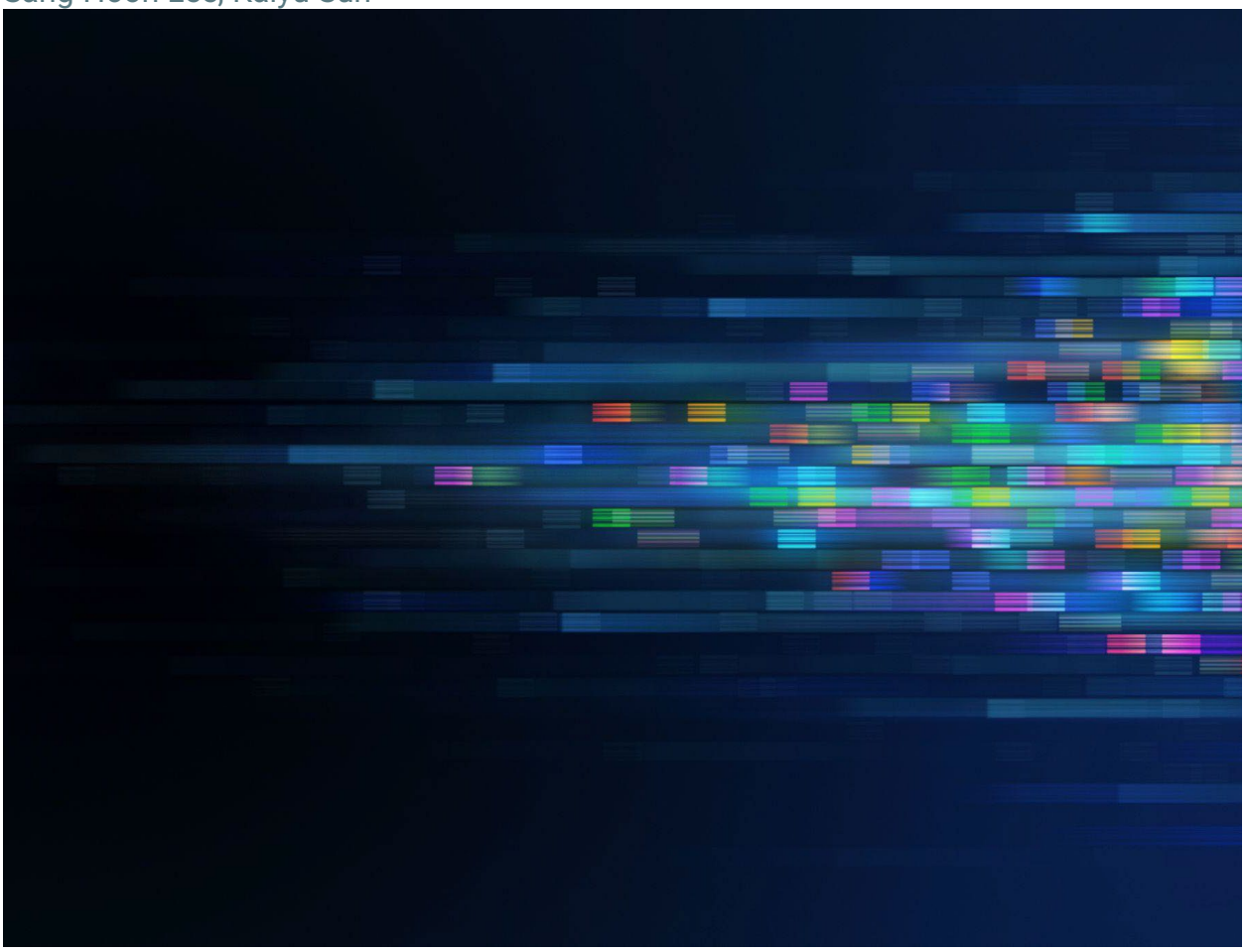
U.S. General Services Administration

BERKELEY LAB

October 12, 2026

Non-Metalized Exterior Sun Control Film

Luís Fernandes, Anothai Thanachareonkit, Taoning Wang, Tammie Yu, Howdy Goudey, Sang-Hoon Lee, Kaiyu Sun



Disclaimer

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor Berkeley Lab, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Berkeley Lab. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or Berkeley Lab.

The work described in this report was funded by the U.S. General Services Administration and the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Acknowledgements

The authors wish to acknowledge the following individuals for their contribution to this project.

- GSA CEBT: Joshua Banis, Kevin Powell, Lindsey Perez, Jessica Higgins, Jonathan Kazmeroff
- DOE: Michael Sheppy, Jeff Wanner
- GSA Region 8: Jamie Whiles, Claire Haight, Tyler Cooper
- Tenfold Information Design Services: Andrea Silvestri, Nicole Howard, Donna Creason
- Occupants of Building 67
- NGS: Mark Carlson
- 3M: Jen Daly
- LBNL: Christian Kohler, Hershow Al-Barazi, Daniel Fuller, Bria Reiniger

For more information contact:

Principal Investigator Name: Luís Fernandes
Lab: Lawrence Berkeley National Laboratory
Email: llfernandes@lbl.gov

GSA's Center for Emerging Building Technology (CEBT) and the Department of Energy's (DOE) Office of Critical Minerals and Energy Innovation enable federal and commercial building owners and operators to make sound investment decisions in next-generation building technologies based on their real-world performance.

Table of Contents

Introduction 4
Executive Summary 4
Background 8
Technology Description 8
M&V Plan 10
Testbed 10
M&V Design 13
Results 16
Quantitative Results 16
Qualitative Results 19
Cost-Effectiveness 23
Conclusion 28
Summary Findings 28
Lessons Learned and Best Practices 29
Key Takeaways 30
Appendix 31
Film solar-optical data 31
Data Sources 32
Whole Building Simulation 33

Introduction

Executive Summary

This study was intended to evaluate the performance of an exterior sun control window film provided by 3M, with field verifications and execution by NGS (the selected film was Exterior Prestige 40), in terms of its ability to reduce the amount of solar radiation transmitted through windows, and therefore reduce space cooling loads, as well as positively impact the experience of occupants in the spaces.

Window films are an established technology for improving the energy and comfort performance of windows without replacing the glazing, especially when it comes to controlling glare and solar heat gains through windows. While most film installed in US commercial buildings is applied to the interior surface of the windows, exterior-mounted film can provide improved sun control performance. Relative to interior-mounted film, it prevents more solar radiation from being absorbed by the glass layer(s) of the window and re-radiated to the interior space as long-wavelength infrared. This is particularly the case for insulated glazing units (IGUs) and even more so for IGUs with tinted glazing.

The film was evaluated at Building 67 of the Denver Federal Center. Built in 1967, it has 14 floors and encompasses 372,000 square feet of office space surrounding the elevator lobby and core area. The existing windows are tinted double-pane with a hard-coat low-e. The demonstration was conducted in two phases. In the first phase, exterior film was installed on the south, west, and east facades of the 12th floor, with the 13th floor serving as baseline for comparison. These areas of the building were chosen because there were frequent complaints about the space being too hot during the cooling season, with blinds being lowered by the occupants in order to reduce solar heat gain through the windows. Following positive feedback from building occupants and the building management team regarding the film on the 12th floor, film was then installed on the south, west, and east facades of the remaining floors. This represented the second phase of the demonstration.

Quantitative performance objectives of the evaluation are shown in Table ES-1, along with the results. Measurements showed a substantial reduction in transmittance solar radiation (averaging 74% throughout a clear sky day in August), showing a clear improvement over the existing windows. An analysis of energy use and peak demand reductions using Energy Plus simulations was conducted for 11 ASHRAE climate zones. Energy use reductions ranged between -2.7% (Duluth, MN) to 7.5% (Phoenix, AZ) in the simulation results, depending on region. Peak energy demand reductions ranged from 6.5% (Houston, TX) to 9.4% (Los Angeles, CA) (electricity), and from -29.1% (Phoenix, AZ) to 3.9% (Baltimore, MD) (gas). Calculated based on annual energy simulations for a medium office building in nearby Boulder, Colorado, the annual energy savings yielded a payback period of 19.32 years, with a saving-to-investment ratio of 0.78 (15 yr expected lifespan). Excluding the costs of any needed heavy equipment (lifts, cranes), the retrofit involves an installed cost of $\$12.9/ft^2$-window and no additional annual maintenance costs. It should be noted that these analyses, using GSA blended energy costs, can significantly underestimate the cost-effectiveness of the film retrofit, due to the fact that they don't take into account the impact of reducing electrical peak demand on the demand charge component of the energy costs. A calculation using typical demand charges for large office buildings in Denver yielded a payback period of 10.51 years and a saving-to-investment ratio of 1.43. The cost-effectiveness metrics obtained for the Denver area, which was where the field test was

conducted, should not be taken as indicative of the film performance in more favorable regions, i.e., regions where cooling is the primary energy concern and hence where this type of film is expected to be more cost-effective.

Qualitative objectives and results are shown in Table ES-2. Installation was quicker than anticipated and did not require significant deviations from GSA's standard practices. One potential caveat was noticed for situations where stepping off of the swing stage might be required. Care is to be taken that applicable safety regulations and procedures are observed. No discernible changes were required in the building's exterior window washing procedure. Evidence from interactions with floor occupants strongly suggests that the film made the space feel cooler during the cooling season without negative impacts during the heating season.

Working with an experienced film installer and conducting pre-installation walkthrough and coordination are important for a trouble-free and quick installation. As exterior installation can involve working at substantial height from the ground, adherence to safety norms and procedures is critical.

This technology is expected to yield the highest benefits where the existing windows are double tinted, in buildings and regions where cooling is the primary energy concern, and wherever there is a high cost to even short-term disturbances to the operation and occupants of the interior of the building.

For comparison purposes, simulation results for the same film when installed on the interior side of a window, are presented in Table ES-1. Energy Plus simulations were conducted across 11 ASHRAE climate zones in order to determine the reductions in energy use and peak demand for a medium office building in Boulder, Colorado. These reductions ranged from -1.2% (Duluth, MN) to 1.7% (Miami, FL), depending on region. Peak energy demand reductions ranged from 0.6% (Seattle, WA) to 2.2% (Boulder, CO) for electricity and from -10.9% (Phoenix, AZ) to 12.5% (Miami, FL) for gas.

Table ES-1. Quantitative objectives and results.

Performance objective	What's being measured	Results
Ultraviolet (UV) transmittance	Ultraviolet (UV) transmittance measured in Lawrence Berkeley National Laboratory's (LBNL) Window Optics Lab	Lower than 0.005
Reduction in transmitted solar radiation	Vertical irradiance (W/m2) measured near the interior surface of the window; measured in-situ using pyranometers.	DFC B67: 43% - 90% (74% average)

Performance objective	What's being measured	Results
Return on investment/pay back	Simple payback, savings to investment ratio (SIR); calculated based on typical installed costs and cost of avoided energy use determined using simulation Baseline: double bronze	**Simulation: Exterior film** Payback: 6.89 yr (Phoenix, AZ) - 34.06 yr (Duluth, MN) SIR (10 yr warranty): 0.29 (Phoenix, AZ) -1.45 (Duluth, MN) SIR (15 yr expected lifespan): 0.44 (Phoenix, AZ) - 2.18 (Duluth, MN) **Simulation: Interior film** Payback: 0 yr (Phoenix, AZ) - 719 yr (Duluth, MN) SIR (15 yr expected lifespan): 0 (Phoenix, AZ) - 0.45 (Duluth, MN)
Reduction in energy use	Energy use (kWh, therm, and/or MJ), comprising HVAC, lighting, and plug loads; direct measurement depends on availability of BAS/EMIS data; indirect assessment through simulation Baseline: double bronze	**Simulation: Exterior film:** (-2.7%, Duluth, MN) - 7.5% (Phoenix, AZ) **Simulation: Interior film:** (-1.2%, Duluth, MN) - 1.7% (Miami, FL)
Reduction in peak energy demand	Energy demand (kW), comprising HVAC, lighting, and plug loads; direct measurement depends on availability of BAS/EMIS data; indirect assessment through simulation Baseline: double bronze	**Simulation: Exterior film** Electricity : 6.5% (Houston, TX)- 9.4% (Los Angeles, CA) Gas : (-29.1%, Phoenix, AZ) - 3.9% (Baltimore, MD) **Simulation: Interior film** Electricity : 0.6% (Seattle, WA) - 2.2% (Boulder, CO) Gas : (-10.9%, Phoenix, AZ) - 12.5% (Miami, FL)

Table ES-2. Qualitative objectives and results.

Performance objective	What's being measured	Results
Ease of installation	GSA observations when working with the installer	Installation quicker than anticipated. 3 days for 1 floor (phase 1), 12 days for 13 floors (phase 2). Two installers were involved. No unusual procedures involved. Care must be taken in observing safety regulations whenever stepping off the swing stage is required.
Ease of maintenance	GSA observations regarding window maintenance and cleaning	No discernible impact on usual window cleaning procedures.
Increased occupant satisfaction	Occupant survey responses; impromptu conversations with occupants; interviews of GSA and HVAC O&M personnel	Surveys (n=33): space cooler during warm/hot weather, light level lower but adequate, reduced glare, most (76%) respondents prefer film to original condition, likely no effect on cell reception. Conversations with O&M personnel indicate a reduction in hot calls. Analysis of hot/cold call data inconclusive due to changes in reporting procedure.

Background

Window films are an established technology for improving the energy and comfort performance of windows without replacing the glazing, especially when it comes to controlling glare and solar heat gains through windows. Films are commercially available across the United States from several major manufacturers.

While most film installed in US commercial buildings is applied to the interior surface of the windows, exterior-mounted film can provide superior sun control performance, since, relative to interior-mounted film, it prevents more solar radiation from being absorbed by the glass layer(s) of the window and re-radiated to the interior space as long-wavelength infrared. This is particularly the case for insulated glazing units (IGUs) and even more so for IGUs with tinted glazing.

Technology Description



Figure 1. The window film is positioned in front of the window, viewed from the interior (left). The film in the roll before the installation (right).

Window films are polymer-based films that can be adhered to glass in order to modify the solar-optical properties of windows. Of the several types of window films, spectrally-selective sun control films have emerged as particularly appealing, as they provide additional sun control when compared to tinted films. From a sun control performance perspective, the ideal placement of window films is on the exterior glass surface of windows. Despite this advantage, exterior films, while available in the market for decades, have lagged significantly in adoption when compared to films for interior mounting. Concerns about durability, shorter manufacturer warranties, and, for multi-story buildings, more complex installation, may have all played a part in this state of affairs.

Spectrally-selective window films traditionally contain a metallic layer that provides them with their special sun control properties. This, for exterior-mounted window films, can be a source of concerns about corrosion. Non-metallic spectrally-selective window films can be corrosion-free and more durable, changing the cost-benefit equation for exterior vs. interior window film retrofits. Although installation can be more complex than for interior films, it is also much less disruptive to building occupants. Non-metallic window films can also avoid interference with cellular communications; such interference can occur when a large proportion of the building envelope contains a metallic layer.

From the energy performance point of view, the main advantage of spectrally-selective exterior films is that they block solar radiation before it reaches the window glass. In comparison to an interior film, the glass

temperature and the amount of heat that is absorbed and re-radiated by the glass towards the building interior are reduced. This difference is most relevant in insulated glazing units (IGUs) that have some kind of tinted glazing, e.g., double bronze IGUs.

M&V Plan

Testbed

Denver Federal Center Building 67 (DFC-67) was built in 1967 and is located in Denver, CO. This high-rise, concrete structure has 14 floors and encompasses 372,000 square feet of office space surrounding the elevator lobby and core area. The existing windows are double-pane tinted with a medium or high solar gain pyrolytic low-emissivity coating. The building's window opening area totals 56,909 square feet, with the distribution by orientation as follows: west: 19,461 square feet, east: 18,406 square feet, north: 9,817 square feet, south: 9,225 square feet. During the first phase of the retrofit demonstration, exterior films were installed on the south, west and east facades of the 12th floor, with the 13th floor serving as baseline for comparison. In the second phase, film was installed on the south, west and east facades of the remaining floors.



Figure 2. Exterior non-metallic films were installed on Denver Federal Center Building 67's 12th floor.

Table 1. Site Criteria

System	Portfolio-Wide Implementation	Testbed Pilot
Facility Characteristics	*Space(s) with significant glazed area/High window-to-wall ratio *Significant cooling demand *Windows either double clear or double tinted	Window-to-wall ratio is appropriate Two floors similar in space utilization, lighting, plug loads, and occupancy (number of people and hours), facade orientation, external shading/obstructions Double-glazed windows, probably tinted, with high solar gain low-emissivity No pre-existing film Glazing facing north, south, east, and west Extensive search did not identify any site suitable for HVAC measurements; simulation approach does not require onsite HVAC data Hard coat, high solar gain low-e windows reduce thermal stress risk due to their primary focus on heat conduction reduction rather than sun control
Location	*Region with significant cooling loads at least part of the year	Denver site has significant cooling required during summer months, at minimum
Occupancy		Site occupancy expected to be stable throughout study
Whole building electricity data		Extensive search did not identify any site suitable for whole building measurements; simulation approach does not require this onsite data
Historical electricity data		Extensive search did not identify any site suitable for whole building measurements; simulation approach does not require this onsite data
Documentation	*Existing window specs (glazing layer(s), gas fill)	Existing window specs not available; in-situ measurements were able to provide sufficient information. HVAC data is not needed due to choosing a simulation approach for determining energy use.
Lighting controls		Lighting system operation is not identical but reasonably similar between floors.

System	Portfolio-Wide Implementation	Testbed Pilot
Automated/operable shading		Operable shading identical between floors.
HVAC		Extensive search did not identify any site suitable for HVAC measurements; simulation approach does not require onsite HVAC data

* nice to have

M&V Design

Performance attributes

The study evaluated the performance of an exterior, spectrally-selective window film based on the following key attributes:

1. Transmitted solar radiation:

- Measurement protocol: In-situ measurements using Apogee Instruments SP-522 pyranometers.
- Variables monitored: Transmitted solar irradiance.
- Duration: Measurements captured over the course of a sunny day.
- Instrumentation: Apogee SP-522 Pyranometers connected to Raspberry Pi data logging equipment.
- Location: Test and reference areas of Building 67.

2. Optical properties of film samples:

- Measurement protocol: Spectral properties (transmittance, reflectance, absorptance) measured in a laboratory setting.
- Variables monitored: Spectral transmittance, reflectance, and absorptance.
- Instrumentation: Perkin-Elmer Lambda 950 spectrometer.
- Location: LBNL's Window Optics Lab.

3. Energy Use:

- Measurement protocol: Computer simulations using EnergyPlus models.
- Variables monitored: Annual energy consumption in kWh; peak annual energy consumption in kW.
- Duration: Simulated operation over a typical year.
- Simulation design: Modified typical DOE prototype medium office building models adapted to different regions.

4. Cost-effectiveness:

- Measurement protocol: Economic analysis using simple payback and savings to investment ratio.
- Variables monitored: Installation costs, energy cost savings, potential operational and maintenance costs.
- Data sources: Installation costs provided by manufacturing and installation partners and GSA local energy cost data.

Testing protocols

1. Transmitted solar radiation testing

- Deploy pyranometers in strategic positions within the test and reference areas of building 67.
- Connect to Raspberry Pi for continuous data logging.
- Ensure data capture over a full sunny day, repeat as necessary in case of inclement weather.

2. Optical measurements

- Prepare film samples and calibrate the spectrometer.
- Conduct measurements under controlled laboratory conditions
- Record spectral properties data for comparison and simulation input.

3. Energy simulation

- Utilize EnergyPlus software to simulate energy use
- Input climatic data specific to relevant zones.
- Run simulations for various scenarios including baseline (no film) and film applied windows.
- Run simulations for scenarios of that film applied on the interior side of windows.

5. Cost-effectiveness analysis

- Gather cost data from partners.
- Calculate simple payback period and savings to investment ratio.
- Incorporate any additional cost factors identified during the study.

Data sources and instrumentation

- Data logging: Apogee SP-522 pyranometers, Raspberry Pi for solar radiation logging.
- Optical properties: Perkin-Elmer Lambda 950 spectrometer for sample spectral data.
- Energy consumption: EnergyPlus software models with DOE prototype medium office building inputs.
- Economic data: Installation and energy costs provided by manufacturers and GSA.

Energy simulation design

- Simulation tool: EnergyPlus
- Model: Modified DOE prototype medium office building
- Climate zones: simulations tailored to various ASHRAE climate zones where GSA offices are located.

Table 2. Energy Modeling Assumptions.

Modeling Attributes	Characteristics
Building Size/Shape	53,628 sf, 3 floors (medium office)
Building Age	Pre 1980
ASHRAE Climate Zones	• 1A (Miami, hot humid) • 2A (Houston, hot humid) • 2B (Phoenix, hot dry) • 3A (Atlanta, mixed humid) • 3B (Las Vegas, mixed dry) • 3C (San Francisco, mixed marine) • 4A (Baltimore, mixed humid) • 4B (Albuquerque, mixed dry) • 4C (Seattle, mixed marine) • 5A (Chicago, cold humid) • 5B (Boulder, cold dry)
Baseline	Double-pane bronze

Results

Quantitative Results

Reduction in transmitted solar radiation

The exterior non-metallic film demonstrates substantial improvements in reducing transmitted solar radiation. Field measurements reveal vertical irradiance reduction ranging from 43% to 90%, averaging 74%, indicating a significant improvement over the existing double-pane low-e tinted windows. This effectively lowers solar heat gain, contributing to improved thermal comfort and cooling energy savings.

According to the measurement of the film properties in the LBNL's Window Optics Lab, the ultraviolet (UV) transmittance of the film is lower than 0.005. Spectral properties (transmittance, reflectance, and absorptance) of the film are plotted in Figure A1 in the Appendix.

Energy simulation

In terms of energy use, results obtained through whole building energy simulation using standard medium office building models indicate a marginal to moderate reduction in energy use ranging from -2.7% (Duluth, MN) to 7.5% (Phoenix, AZ), and peak energy demand reductions ranging from 6.5% (Houston, TX) to 9.4% (Los Angeles, CA), and from -29.1% (Phoenix, AZ) to 3.9% (Baltimore, MD) for electricity and gas, respectively. These results are regionally dependent, and savings increase wherever more cooling is prevalent throughout the year. In terms of financial feasibility, payback periods range from 6.89 to 34.06 years, with the savings to investment ratio ranging from 0.44 and 2.18 (15 yr expected lifespan). This variation underscores the importance of considering local energy cost and habitual weather before implementation.

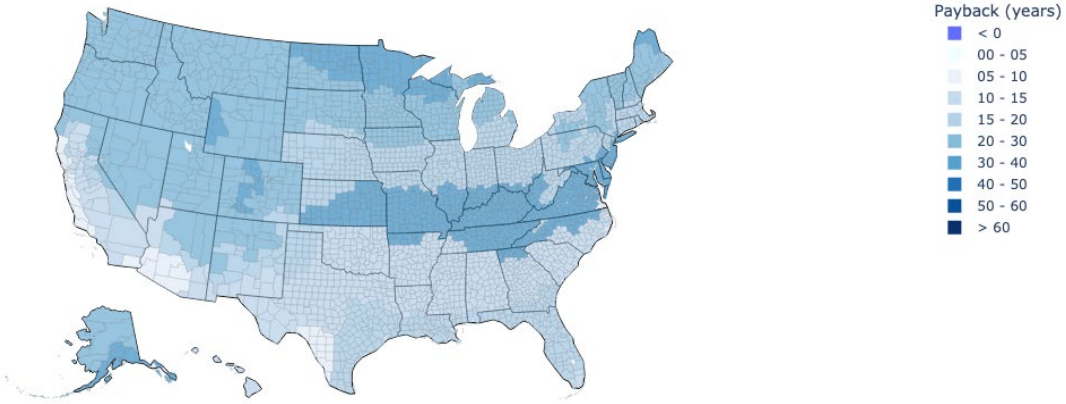


Figure 3: Payback by ASHRAE climate zones: double clear bronze window with film applied on the exterior.

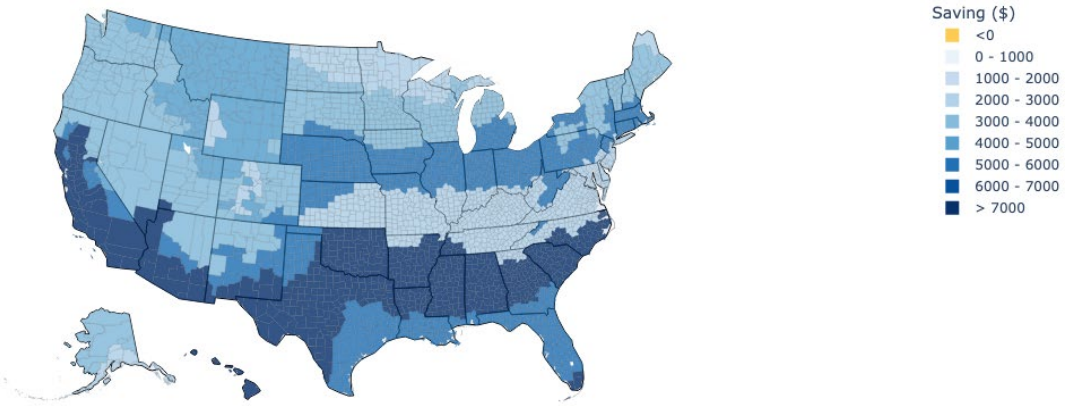


Figure 4: Annual cost savings by ASHRAE climate zones: double clear bronze window with film applied on the exterior.

Overall, the exterior film offers marked improvement in solar radiation control and holds considerable promise for significant energy savings. Confidence in performance is solid, particularly in terms of solar irradiance reduction, and the promising energy use reduction indicates valuable gains in energy management.

In terms of energy use with film applied on the interior side, results obtained through whole building energy simulation using standard medium office building models indicate a reduction in energy use ranging from -1.2% (Duluth, MN) to 1.7% (Miami, FL), and peak energy demand reductions ranging from 0.6% (Seattle, WA) to 2.2% (Boulder, CO) and from -10.9% (Phoenix, AZ) to 12.5% (Miami, FL) for electricity and gas, respectively. These results are regionally dependent, and savings increase wherever more cooling is prevalent throughout the year. In terms of financial feasibility, payback periods range from zero to 719 years, with the savings to investment ratio ranging from zero to 0.45 (assuming a 15-year lifespan). It should be noted that the habitually cold weather in some of these regions means that the use of the film would not be expected to be cost-effective. Very long payback periods, as well as the occurrence of negative savings (i.e., increases in energy use) is to be expected for those regions. These regions were included in the analysis in order to obtain a complete nationwide picture of film performance. The Key Takeaways section of this report details the regions where this film is expected to be cost-effective.

Table 3. Energy and financial impacts summary.

Performance objective	What's being measured	% Savings Compared to Baseline
Ultraviolet (UV) transmittance	Ultraviolet (UV) transmittance measured in the LBNL's Window Optics Lab	Lower than 0.005

Performance objective	What's being measured	% Savings Compared to Baseline
Reduction in transmitted solar radiation	Vertical irradiance (W/m2) measured near the interior surface of the window; measured in-situ using pyranometers.	DFC B67: 43% - 90% (74% average)
Return on investment/pay back	Simple payback, savings to investment ratio (SIR); calculated based on typical installed costs and cost of avoided energy use determined using simulation Baseline: double bronze	**Simulation: Exterior film** Payback: 6.89 yr (Phoenix, AZ) - 34.06 yr (Duluth, MN) SIR (10 yr warranty): 0.29 (Phoenix, AZ) -1.45 (Duluth, MN) SIR (15 yr expected lifespan): 0.44 (Phoenix, AZ) - 2.18 (Duluth, MN) **Simulation: Interior film** Payback: 0 yr (Phoenix, AZ) - 719 yr (Duluth, MN) SIR (15 yr expected lifespan): 0 (Phoenix, AZ) - 0.45 (Duluth, MN)
Reduction in energy use	Energy use (kWh, therm, and/or MJ), comprising HVAC, lighting, and plug loads; direct measurement depends on availability of BAS/EMIS data; indirect assessment through simulation Baseline: double bronze	**Simulation: Exterior film:** (-2.7%, Duluth, MN) - 7.5% (Phoenix, AZ) **Simulation: Interior film:** (-1.2%, Duluth, MN) - 1.7% (Miami, FL)
Reduction in peak energy demand	Energy demand (kW), comprising HVAC, lighting, and plug loads; direct measurement depends on availability of BAS/EMIS data; indirect assessment through simulation Baseline: double bronze	**Simulation: Exterior film** Electricity : 6.5% (Houston, TX) - 9.4% (Los Angeles, CA) Gas : (-29.1%, Phoenix, AZ) - 3.9% (Baltimore, MD) **Simulation: Interior film** Electricity : 0.6% (Seattle, WA)- 2.2% (Boulder, CO) Gas : (-10.9%, Phoenix, AZ) - 12.5% (Miami, FL)

Qualitative Results

Ease of installation

Overall, the process for installing window film involves measuring the window and cutting the film to measure, thoroughly washing the windows with a soapy water solution, and applying the film. In the case of exterior film the main differences are the need to access the windows on the outside of the building, the fact that, due to the window being exposed to the elements, the washing process may need to be more thorough, and that no moving/shielding furniture and surfaces from water splashes is required. Depending on the building height, fall protection and access to a lift or swing stage may also be needed.

Observational data regarding the installation process of the window film was gathered from GSA and building maintenance personnel. Film installation on the 12th floor of Building 67 took less than three days, which was significantly faster than anticipated. GSA performed a walkthrough with the contractor during the week prior to installation. The process also involved advance coordination regarding swing stage access. Pre-installation coordination and preparation did not involve any particularly unusual processes from the GSA standpoint. The exterior window geometry of Building 67, with windows inset from the facade, required film installation contractor personnel to step onto the exterior ledge; where this is needed, it is important that this is done according to applicable safety regulations. Outdoor conditions required for installation include: no rain, no high winds, and outdoor air temperature between 45 and 95 degrees Fahrenheit. Installation on the rest of the building's windows took place in approximately 19 calendar days (12 working days), which was significantly shorter than the anticipated duration (48 calendar days).

Ease of maintenance

The exterior window surface in Building 67 is cleaned annually, usually during the summer. Since the film was installed, cleaning has proceeded without any issues or deviations from the usual procedures. The film manufacturer recommends soapy water as a cleaning agent, and that cleaning products with ammonia should not be used. Scrubbing pads should also not be used on windows with film.

Occupant satisfaction

After the film was installed on all floors, a survey of the occupants was conducted, addressing thermal and visual comfort, general satisfaction, preference between film and original window configurations, interference with cell phone reception, and allowing occupants to provide any additional comments regarding the film. Forty-five responses were recorded, 33 of them from occupants in the east, west, and south areas of the floor - the latter were considered in the analysis shown below.

Environmental quality

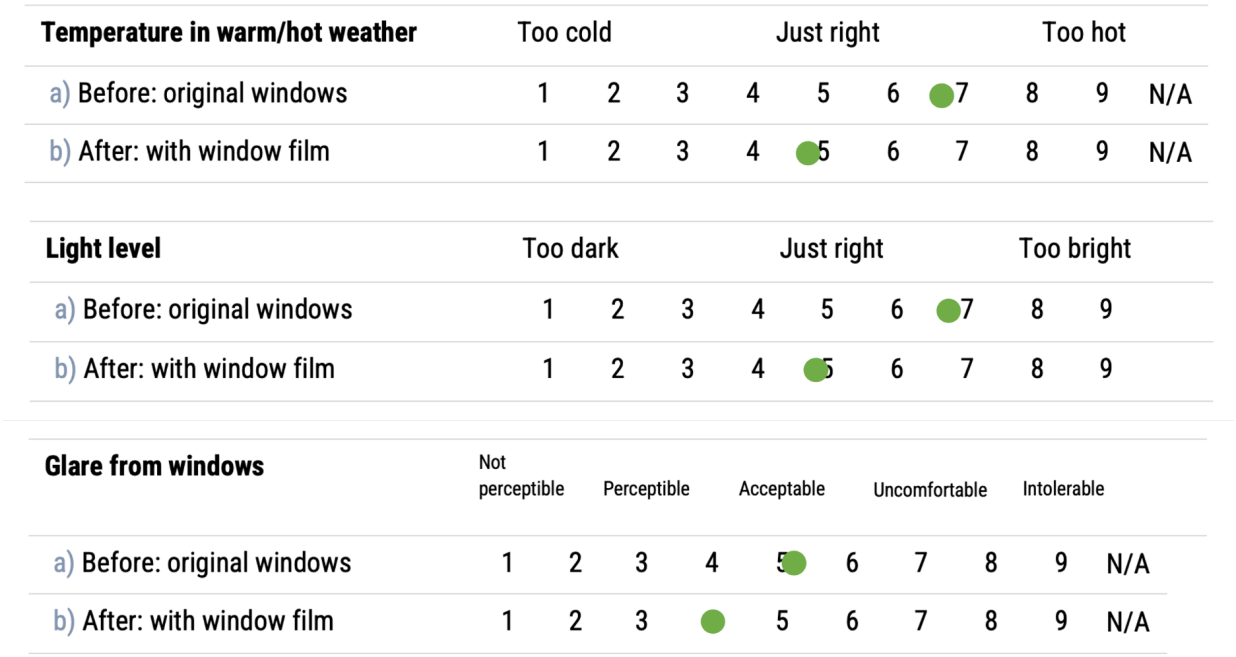


Figure 5. Averages of occupant responses to indoor environmental quality questions.

Occupants found the space less hot during warm/hot weather after the film was installed (Figure 5). The average pre-installation response was halfway between "just right" and "too hot"; the average post-installation response was "just right". Similarly, the space was found less bright after the film was installed, with the average response after the installation being just under "just right". Glare from the windows was also reduced after the film installation, from just under "acceptable" towards "perceptible".

The differences between the pre- and post-installation average responses were found to be statistically significant at a level greater than 99%, using a two-tailed, paired t-test.

Satisfaction and preference

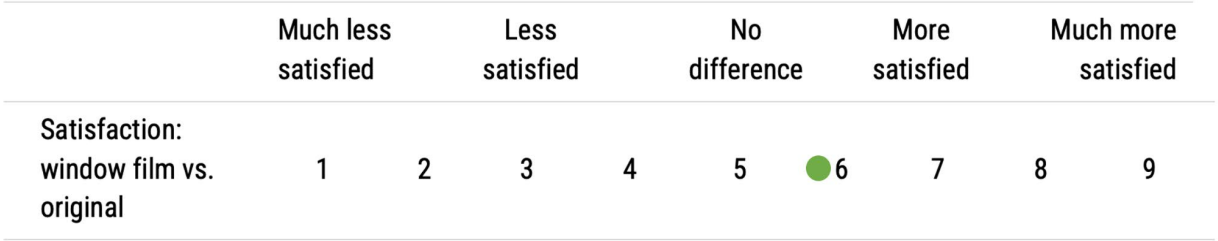


Figure 6. Average occupant response regarding overall satisfaction with film versus original window condition.

The average occupant response was between "no difference" and "more satisfied" (Figure 6). While this may suggest that occupants were, on average, slightly more satisfied with the film than with the original window condition, the 95% confidence interval from a one-sample t-test goes from 4.87 to 6.81.

Statistically, it is inconclusive that occupant satisfaction increased. However, when asked “Overall, would you prefer the windows in your area to have film or left in their original condition?”, out of 25 responses, 19 chose the film condition. Overall, these results strongly suggest that occupants preferred the film to the original window condition.

Cell reception

When asked “Did you notice any change in cell reception after the installation of the window film?”, 23 participants responded “no”, one responded “yes”, and another one “not sure”. This is consistent with the expectation that a non-metallic window film would not impact cell reception in the space.

Occupant comments

Occupants provided additional comments on the survey. There were several generally positive comments regarding the film making the space more comfortable. It was noted that, after the film was installed, the space was still, at times, uncomfortable (too hot, too cold, too dark, or there was too much glare). Overall, there were two comments regarding visible artifacts attributed to the film (bubbles, scratches, the latter visible when the sun was low).

A discussion session was offered to survey respondents who indicated their availability for a follow-up conversation. Three respondents participated. Topics surfaced during these conversations included:

- Neither the presence of the film nor the installation were visible to the occupants.
- Although the film reduces glare, shades are still needed when the sun is low.
- Hot calls reported directly to the tenant’s building management team went down after film installation. However, this may have been confounded by changes in GSA’s hot/cold call procedure throughout this study.

Hot/cold calls

Hot and cold call data from March 2022 to February 2026 was analyzed in order to discern whether there was a measurable impact from film installation. Overall, results indicated an increase in both cold and hot calls in the whole building. However, the process for hot/cold calls changed during the study. Starting sometime in 2024, which is around the time when the film was installed in the whole building, the process was changed to allow building occupants to input hot/cold calls directly in the building’s work request system. It is reasonable to expect that this, on its own, would lead to an increase in the frequency of hot/cold calls. The results of the analysis of hot/cold call data are, therefore, inconclusive.

Table 4. Qualitative results summary.

Objective	What Is Being Measured?	Results
Ease of installation	GSA observations when working with the installer	Whole-building installation quicker than anticipated (19 calendar days, 12 actual, vs. planned 48 calendar days) for 2 installers. No unusual procedures involved. Care must be taken in observing safety regulations whenever stepping off the swing stage is required.
Ease of maintenance	GSA observations regarding window maintenance and cleaning	No discernible impact on usual window cleaning procedures.
Increased occupant satisfaction	Occupant survey responses; impromptu conversations with occupants; interviews of GSA and HVAC O&M personnel	Surveys (n=33): space cooler during warm/hot weather, light level lower but adequate, reduced glare, most (76%) respondents prefer film to original condition, likely no effect on cell reception. Conversations with O&M personnel indicate a reduction in hot calls. Analysis of hot/cold call data inconclusive due to changes in reporting procedure.

Cost-Effectiveness

Based on annual energy simulations for a medium office building in Boulder, Colorado - the same ASHRAE climate zone as Building 67 - with double bronze windows, the cost-effectiveness analysis of retrofitting the building with exterior window film reveals several key insights. The retrofit involves a labor and materials cost totaling $12.9 per square foot of window. No additional annual maintenance costs are incurred post-retrofit.

The simulations show a reduction in annual electricity energy consumption from 869,807 kWh to 818,207 kWh, equating to a savings of 51,600 kWh per year. When broken down per square foot of window, the electricity energy consumption decreases from 16.22 kWh/ft²/year to 15.26 kWh/ft²/year, a reduction of 0.96 kWh/ft²/year. In monetary terms, at an electricity energy cost of $0.11 per kWh, this retrofit translates to annual cost savings of $5,676. For gas energy consumption, the simulations show an increase in annual gas energy consumption from 110,014 kWh (3,754 therms) to 147,574 kWh (5,035 therms), equating to an increase of gas energy use of 37,560 kWh (1,282 therms) per year. When broken down per square foot of window, the gas energy consumption increases from 2.05 kWh/ft²/year (0.07 therm/ft²/year) to 2.75 kWh/ft²/year (0.09 therm/ft²/year), an increase of 0.70 kWh/ft²/year (0.02 therm/ft²/year). In monetary terms, at a gas energy cost of $0.0262 per kWh ($0.77 per therm), this retrofit translates to an annual cost increase of $985. The retrofit results in an annual savings of $4,691 when considering the combined costs of electricity and gas. The payback period for this retrofit is 19.32 years, with a saving-to-investment ratio of 0.78 (15 yr expected lifespan).

In addition, simulation results using the equivalent film product for interior installations show a reduction in annual electricity energy consumption from 869,807 kWh to 862,163 kWh, equating to a savings of 7,644 kWh per year. When broken down per square foot of window, the electricity energy consumption decreases from 16.22 kWh/ft²/year to 16.08 kWh/ft²/year, a reduction of 0.14 kWh/ft²/year. In monetary terms, at an electricity energy cost of $0.11 per kWh, this retrofit translates to annual cost savings of $841. For gas energy consumption, the simulations show an increase in annual gas energy consumption from 110,014 kWh (3,754 therms) to 119,135 kWh (4,065 therms), equating to an increase of gas energy use of 9,121 kWh (311 therms)per year. When broken down per square foot of window, the gas energy consumption increases from 2.05 kWh/ft²/year (0.09 therm/ft²/year) to 2.22 kWh/ft²/year (0.08 therm/ft²/year), an increase of 0.17 kWh/ft²/year (0.01 therm/ft²/year).

The interior film retrofit involves a labor and materials cost totaling $11.85 per square foot of window; there are no additional annual maintenance costs incurred post-retrofit. In monetary terms, at a gas energy cost of $0.0262 per kWh ($0.77 per therm), this retrofit translates to an annual cost increase of $239. The payback period for this retrofit is 138.41 years[1], with a saving-to-investment ratio of 0.11 (15 yr expected lifespan).

When interpreting these results, it should be noted that they do not take into account the benefits from reducing peak electrical demand. This is due to the fact that electricity costs were calculated based on cost

[1] This long payback period occurs mainly because the region where the field demonstration was conducted has significant heating needs and should not be construed as representative of the film performance in more suitable regions, as detailed in the Key Takeaways section of this report.

per kWh and do not include demand charges. In commercial buildings, demand charges can be a significant component of electricity costs, and these results likely underestimate the cost-effectiveness of sun control window films. In order to estimate the magnitude of this underestimation, an analysis was conducted using the utility rates applicable to a large commercial building in Downtown Denver (Secondary General electricity rate, and CLG rate for natural gas). With these rates, installing exterior film results in annual electricity cost savings of $9,329 for electricity and a corresponding natural gas cost increase of $705. The net cost savings are $8,625, yielding a substantially shorter payback period of 10.51 years and a savings-to-investment ratio of 1.43.

Table 5. Economic assessment summary (film applied on the exterior side of the windows).

Metric	Baseline (Before)	Tested Technology (After)[1]	Difference
Installed cost per ft²-window	N/A	$12.9	$12.9
Annual Energy Consumption	Electricity: 869,807 kWh/yr Gas: 110,014 kWh/yr (3,754 therm/yr)	Electricity: 818,207 kWh/yr Gas: 147,574 kWh/yr (5,035 therm/yr)	Electricity: 51,600 kWh/yr Gas: -37,560 kWh/yr (-1,282 therm/yr)
Annual Energy Consumption per ft²-floor	Electricity: 16.22 kWh/ft2/yr Gas: 2.05 kWh/ft2/yr (2.05 therm/ft2/yr)	Electricity: 15.26 kWh/ft2/yr Gas: 2.75 kWh/ft2/yr (2.75 therm/ft2/yr)	Electricity: 0.96 kWh/ft2/yr Gas: -0.70 kWh/ft2/yr (0.70 therm/ft2/yr)
Testbed Annual Energy Costs ($0.11/kWh (electricity), $0.0262/kWh (gas))	Electricity: 95,679 $/yr Gas: 2,885 $/yr Total: 98,563 $/yr	Electricity: 90,003 $/yr Gas: 3,869 $/yr Total: 93,872 $/yr	Electricity: 5,676 $/yr Gas: -985 $/yr Total: 4,691 $/yr
GSA Annual Energy Costs Cost-effective in ASHRAE climate zones 1A, 2B, 3A, 3B and 3C using GSA regional blended utility rates ($0.10–	Electricity: 103,198 - 208,234 $/yr Gas: 413 - 1,269 $/yr Total: 104,145 - 208,647	Electricity: 95,514 - 196,726 $/yr Gas: 493 - 1,715 $/yr Total: 96,481 - 197,219	Electricity: 7,370 - 13,312 $/yr Gas: (-446) - (-20) $/yr

Metric	Baseline (Before)	Tested Technology (After)[1]	Difference
Installed cost per ft^2-window	N/A	$12.9	$12.9
$0.27/kWh electricity; $0.0258–$0.1441/kWh gas) **Applicable to ASHRAE climate zones 1A, 2B, 3A, 3B and 3C**	$/yr	$/yr	Total: 7,048 - 13,164 $/yr

Simple Payback (testbed)	19.32 yrs
Savings-to-Investment Ratio (testbed)	0.78 (15 yr expected lifespan)
Simple Payback Range (GSA average) **Applicable to ASHRAE climate zones 1A, 2B, 3A, 3B and 3C**	6.89 - 12.86 yrs
Savings-to-Investment Ratio Range (GSA average) **Applicable to ASHRAE climate zones 1A, 2B, 3A, 3B and 3C**	1.17 - 2.18 (15 yr expected lifespan)

Table 6. Economic assessment summary (film applied on the interior side of the windows).

Metric	Baseline (Before)	Tested Technology (After)[1]	Difference
Installed cost per ft^2-window	N/A	$11.85	$11.85
Annual Maintenance	0 $/yr	0 $/yr	0 $/yr
Annual Energy Consumption	Electricity: 869,807 kWh/yr Gas: 110,014 kWh/yr (3,754 therm/yr)	Electricity: 862,163 kWh/yr Gas: 119,135 kWh/yr (4,065 therm/yr)	Electricity: 7,644 kWh/yr Gas: -9,121 kWh/yr (311 therm/yr)
Annual Energy Consumption per ft^2-floor	Electricity: 16.22 kWh/ft2/yr Gas: 2.05 kWh/ft2/yr (2.05 therm/ft2/yr)	Electricity: 16.08 kWh/ft2/yr Gas: 2.22 kWh/ft2/yr (2.22 therm/ft2/yr)	Electricity: 0.14 kWh/ft2/yr Gas: -0.17 kWh/ft2/yr (0.17 therm/ft2/yr)
Annual Energy Costs (GSA average @ $0.11/kWh (electricity), $0.0262/kWh (gas))	Electricity: 95,679 $/yr Gas: 2,885 $/yr Total: 98,563 $/yr	Electricity: 94,838 $/yr Gas: 3,124 $/yr Total: 97,962 $/yr	Electricity: 841 $/yr Gas: -239 $/yr Total: 602 $/yr
Annual Energy Cost Range (GSA average @ $0.09 - 0.27 /kWh (electricity), $0.0216 - 0.0398/kWh (gas)) **Applicable to ASHRAE climate zones 1A, 2B, 3B and 3C**	Electricity: 103,198 - 208,234 $/yr Gas: 413 - 1,269 $/yr Total: 104,145 - 208,647 $/yr	Electricity: 101,465 - 206,574 $/yr Gas: 428 - 1,366 $/yr Total: 102,415 - 207,002 $/yr	Electricity: 1,008 - 2,506 $/yr Gas: (-98) - (-2) $/yr Total: 935 - 2,477 $/yr

Simple Payback (testbed)	138.41 yrs
Savings-to-Investment Ratio (testbed)	0.11 (15 yr expected lifespan)

Simple Payback (GSA average) **Applicable to ASHRAE climate zones 1A, 2B, 3A, 3B and 3C**	33.62 - 89.03 yrs
Savings-to-Investment Ratio (GSA average) **Applicable to ASHRAE climate zones 1A, 2B, 3A, 3B and 3C**	0.17 - 0.45 (15 yr expected lifespan)

Conclusion

Summary Findings

A demonstration was conducted at the Denver Federal Center (DFC) in Denver, CO, in a 1967 large office building (Building 67) with double-pane bronze windows. In the first phase of the evaluation, exterior window film was installed on the south, west and east facades of the 12th floor, with the 13th floor serving as baseline for comparison. In the second phase, the film was installed on the south, west and east facades of the remaining floors. The film's optical properties were measured in LBNL's Window Optics Lab, showing UV transmittance of less than 0.005, visible transmittance of 0.43, and solar transmittance of 0.25. The quantitative objectives of this study were to determine whether exterior window film retrofitted in an existing commercial building resulted in decreased transmitted solar radiation, as well as to evaluate energy use reductions, peak energy demand reductions and return on investment/payback. The qualitative objectives of this study were ease of installation, ease of maintenance, and occupant satisfaction.

Reduction in transmitted solar radiation

During a day's monitoring, Apogee Instruments SP-522 pyranometers, connected to Raspberry Pi data logging equipment, were placed adjacent to the windows from the interior, measuring transmitted vertical solar radiation on each floor and side.

According to this measurement data, exterior films reduce transmitted solar radiation substantially. The vertical irradiance reduction ranged from 43% to 90%, averaging 74%, showing a significant improvement over the existing tinted low-e double-pane windows. This reduction in solar heat gain is expected to lead to improved thermal comfort and energy savings during the cooling season.

Energy use and peak demand reduction

An important benefit of the exterior window film is that it offers greater energy efficiency than the existing windows. Energy use and peak demand reductions were determined using Energy Plus simulations for 11 ASHRAE climate zones. Energy use reductions ranged between -2.7% (Duluth, MN) and 7.5% (Phoenix, AZ) in the simulation results, depending on region. Peak energy demand reductions ranged from (electricity) 6.5% (Houston, TX) to 9.4% (Los Angeles, CA), and from (gas) -29.1% (Phoenix, AZ) to 3.9% (Baltimore, MD).

Simulations of interior window films showed generally smaller energy use reductions across 11 ASHRAE climate zones when compared to exterior films. Energy use reductions range between -1.2% (Duluth, MN) and 1.7% (Miami, FL), depending on region. There is also variability in peak energy demand reductions, ranging from 0.6% (Seattle, WA) to 2.2% (Boulder, CO) (electricity), and from -10.9% (Phoenix, AZ) to 12.5% (Miami, FL) (gas).

Return on investment and payback

Calculated based on annual energy simulations for a medium office building in Boulder, Colorado, the annual energy savings could yield a payback period of 19.32 years, with a saving-to-investment ratio of 0.78 (15 yr expected lifespan). The retrofit involves an installed cost of $12.90/ft^2-window, and no additional annual maintenance costs. By not taking into account the effect of reduced peak electrical demand, it is very likely that this analysis using blended energy cost data underestimates the cost-effectiveness of the exterior window film. Repeating this analysis using the demand chargers for a building in Downtown Denver - a more typical situation for federal office buildings than Building 67's situation in the Denver Federal Center - yields a payback period of 10.51 years and a saving-to-investment ratio of 1.43.

Ease of installation

Installation was quicker than anticipated (two installers installed film on thirteen floors, taking 19 calendar days vs. scheduled 48 calendar days) and did not require significant deviations from GSA's standard practices. One potential caveat was noticed for situations where stepping off of the swing stage might be required. Care is to be taken that applicable safety regulations and procedures are observed.

Ease of maintenance

No discernible changes were required in the building's exterior window washing procedure. The procedure already used soapy water, a cleaning agent approved by the film manufacturer, and did not include the use of abrasive tools, such as harsh scrubbing sponges. At the end of the life of the film it can be removed. This process is usually significantly faster than film installation although, for very old film, it is possible that the removal process is relatively time consuming. In either case, removal by professional film installers is recommended.

Occupant experience

Results from an occupant survey and follow-up conversations elicited that the space felt cooler during hot/warm weather, the space felt less bright, glare from the windows was reduced, occupants generally preferred the windows with the film versus the original windows, there was no impact on cell reception, and the film was generally visually unnoticed by the building occupants, although a minority of occupants attributed visible artifacts to the film.

Lessons Learned and Best Practices

As with interior film, working with an experienced film installer will increase the likelihood of a trouble-free installation. Performing a walkthrough and coordinating swing stage access prior to installation will tend to reduce installation time. Manufacturer recommendations for installation and maintenance should be adhered to. Compatibility of films with existing windows can vary, depending on specific characteristics of the existing windows, such as orientation, tint, and type and position of low-e coating(s); it is important to observe manufacturer and installer recommendations in this regard. As for the installation process, a common recommendation is to install when there is no rain or strong winds, and outdoor air temperature is above freezing (e.g., between 45 and 95 degrees Fahrenheit). Mild cleaning agents such as soapy water are recommended and ammonia should not be used. Sharp tools or abrasive scrubbing devices should also not

be used. There are situations where the surface of the window will not be sufficiently accessible from a swing stage. Applicable safety regulations and procedures should be taken into account when planning and executing exterior film installation.

Key Takeaways

From a cost-effectiveness standpoint, this film is most advantageous for buildings with non-low-e clear or tinted double-pane windows in regions where cooling is the primary concern (e.g., ASHRAE climate zones 1A, 2B, 3A, 3B, 3C). They may still be appropriate in colder regions where heating penalties are not a major concern; for example, if the heating source is inexpensive when compared to conventional combustion or electric sources,[2] as well as in buildings where electrical demand charges are a significant component of the total energy cost. As with other window retrofits, the impacts of exterior sun control films will be more evident in buildings that have higher window-to-wall ratio and a high ratio of perimeter-to-core floor area, i.e., wherever the shape of the floor plate is relatively narrow. As installation can be entirely performed from the outside of the building, the benefits of exterior film will be highest for applications that have a high cost to disruptions to the interior of the building and wherever installation does not require rental of additional heavy equipment (e.g., lift or crane, versus an existing swing stage).

[2] One example is when waste heat from a nearby industrial or power generation facility is used for campus or district heating.

Appendix

Film solar-optical data

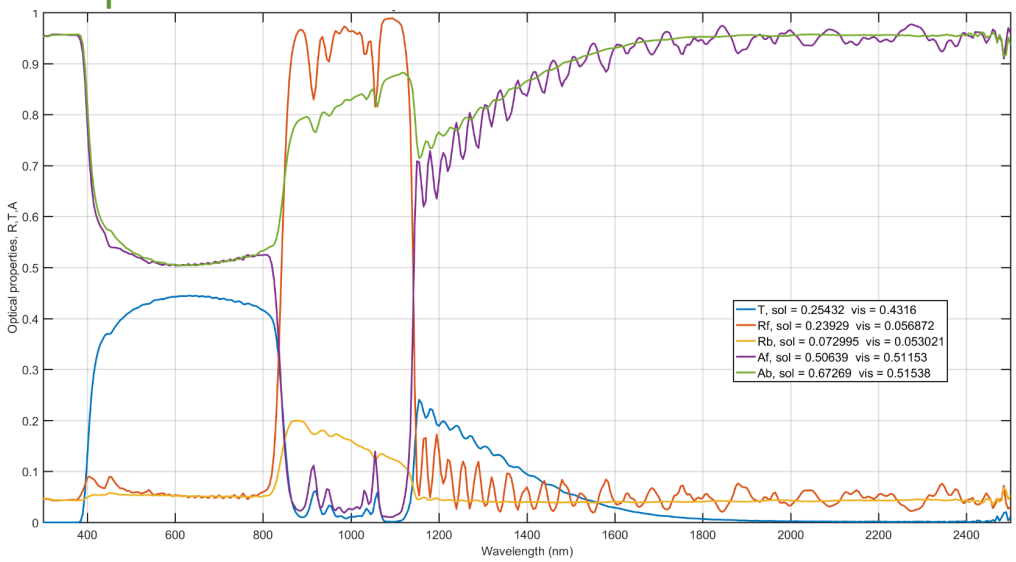


Figure A1. Spectral properties of a film sample of the same kind that was installed in Building 67. Data from measurements in the LBNL's Window Optics Lab.

Data Sources



Figure A2. An Apogee Instruments SP-522 set up at the Denver Federal Center Building 67 (DFC-67) in order to measure solar irradiance transmitted through a window.

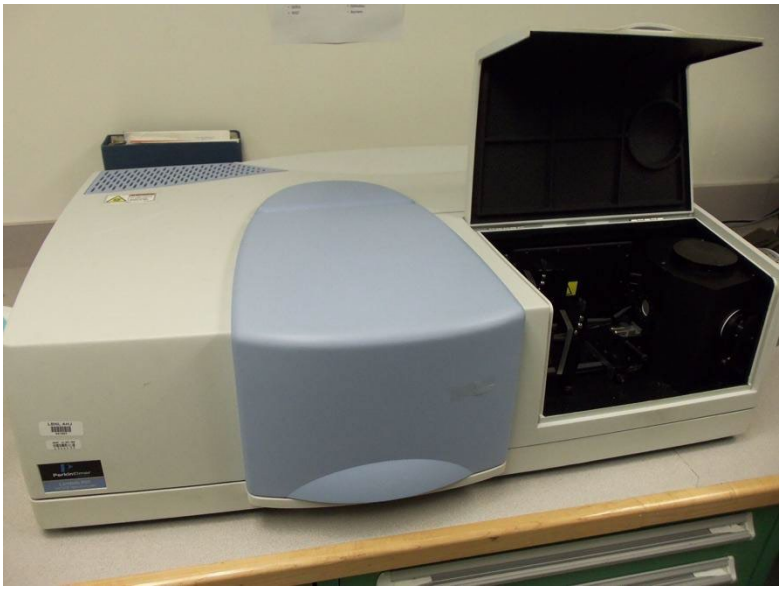


Figure A3. Perkin-Elmer Lambda 950 spectrometer at LBNL's Window Optics Lab.

Whole Building Simulation

Energy simulation (DOE prototype)

Simulations were performed with the EnergyPlus simulation tool for double bronze glazing both with and without the exterior sun control film. Window properties for modeling were determined using LBNL's WINDOW software and measured spectral properties of a film sample.

Table A1. Modeling Assumptions.

Modeling Attributes	Characteristics
Building Size/Shape	53,628 sf, 3 floors (medium office)
Building Age	Pre 1980
ASHRAE Climate Zones	• 1A (Miami, hot humid) • 2A (Houston, hot humid) • 2B (Phoenix, hot dry) • 3A (Atlanta, mixed humid) • 3B (Las Vegas, mixed dry) • 3C (San Francisco, mixed marine) • 4A (Baltimore, mixed humid) • 4B (Albuquerque, mixed dry) • 4C (Seattle, mixed marine) • 5A (Chicago, cold humid) • 5B (Boulder, cold dry)
Baseline	Double-pane bronze

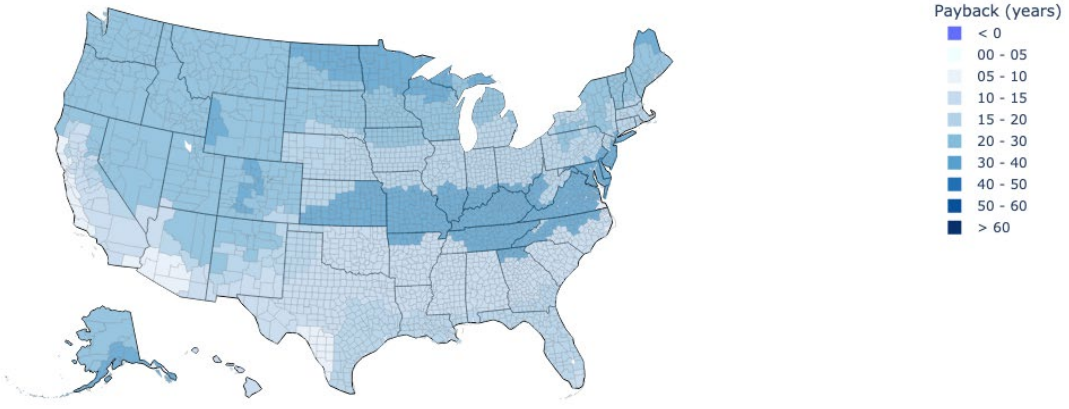


Figure A4: Payback by ASHRAE climate zones: double clear bronze window with film applied on the exterior.

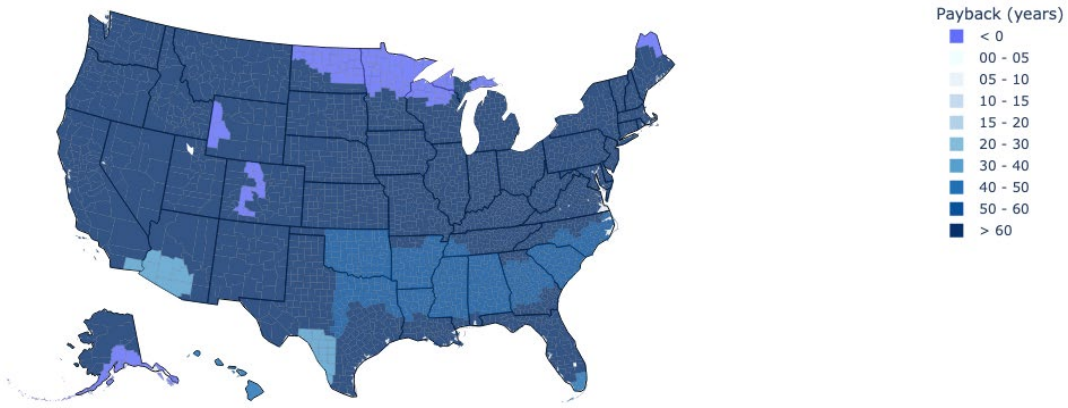


Figure A5: Payback by ASHRAE climate zones: double clear bronze window with film applied on the interior.

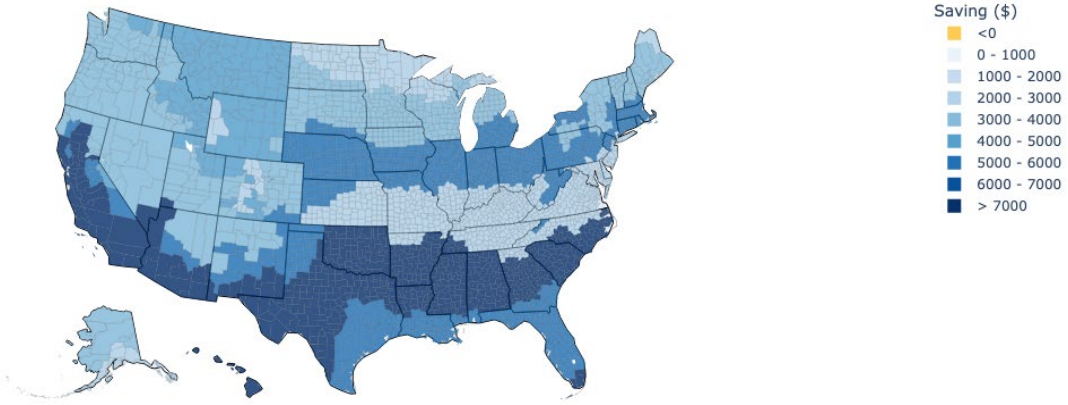


Figure A6: Energy cost savings by ASHRAE climate zones: double clear bronze window with film applied on the exterior.

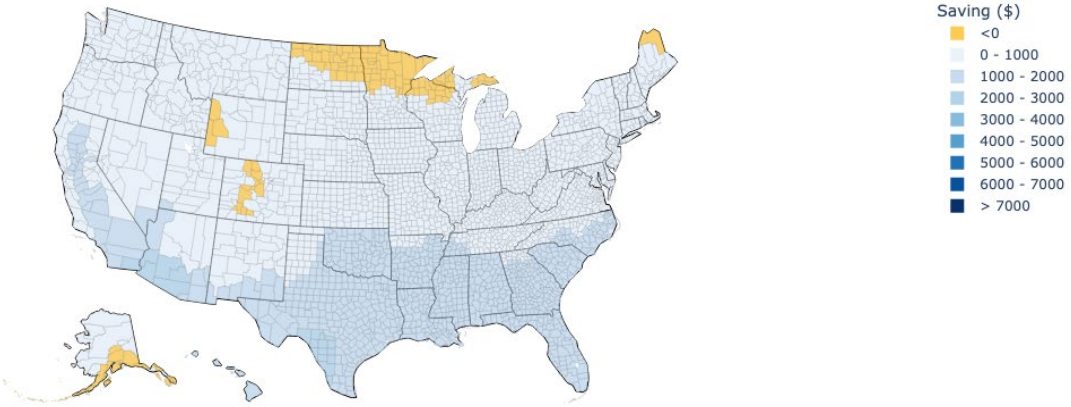
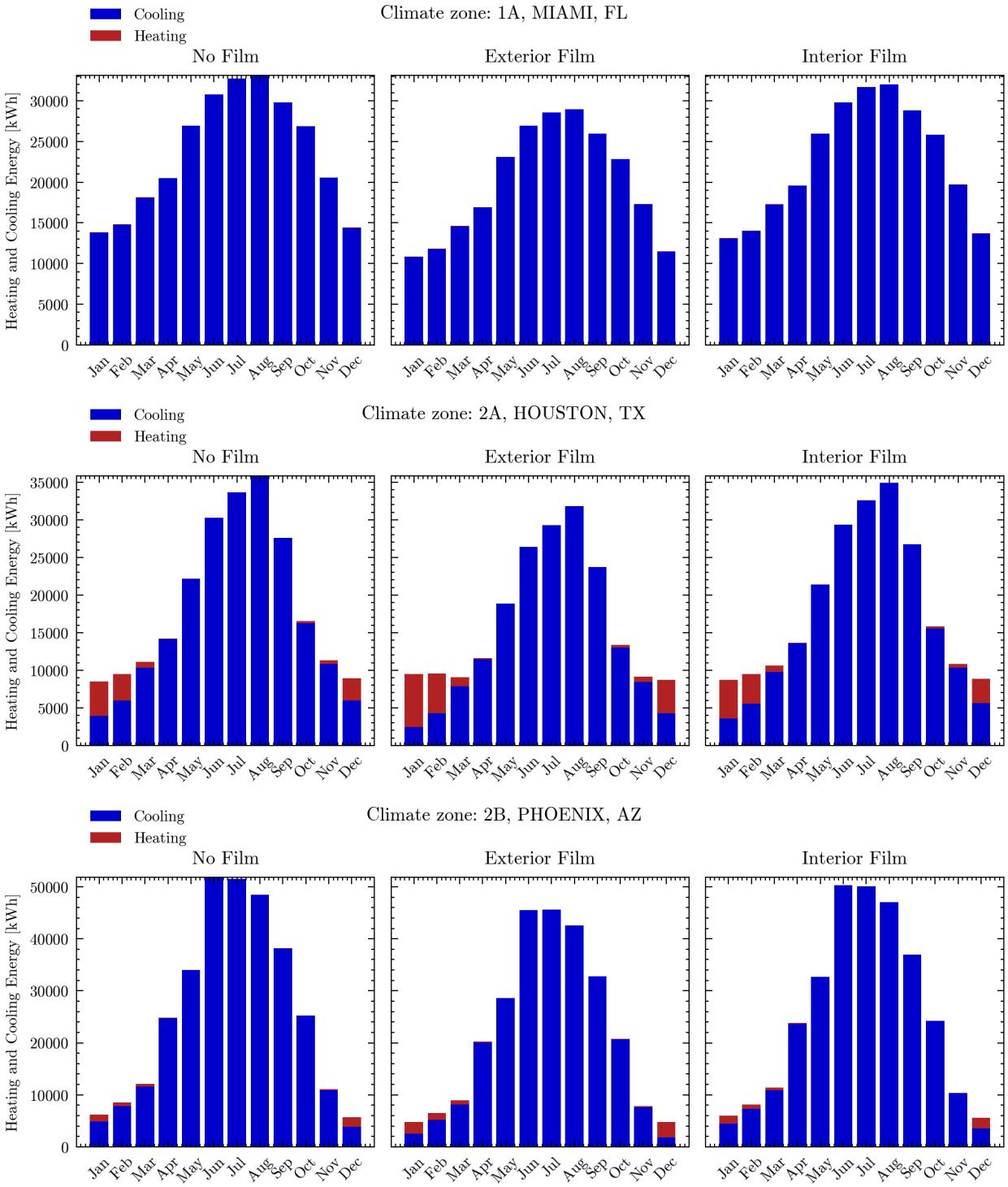
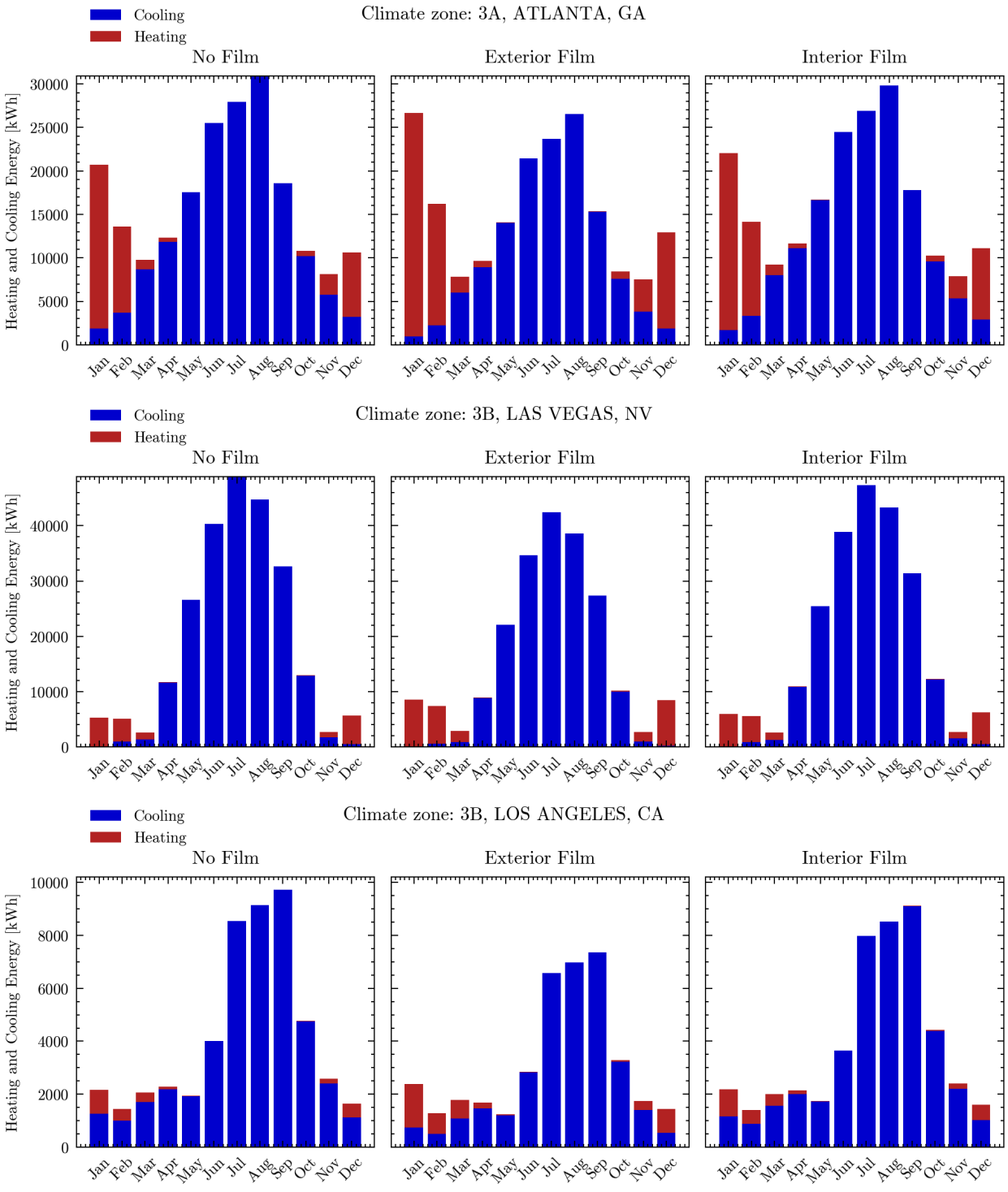
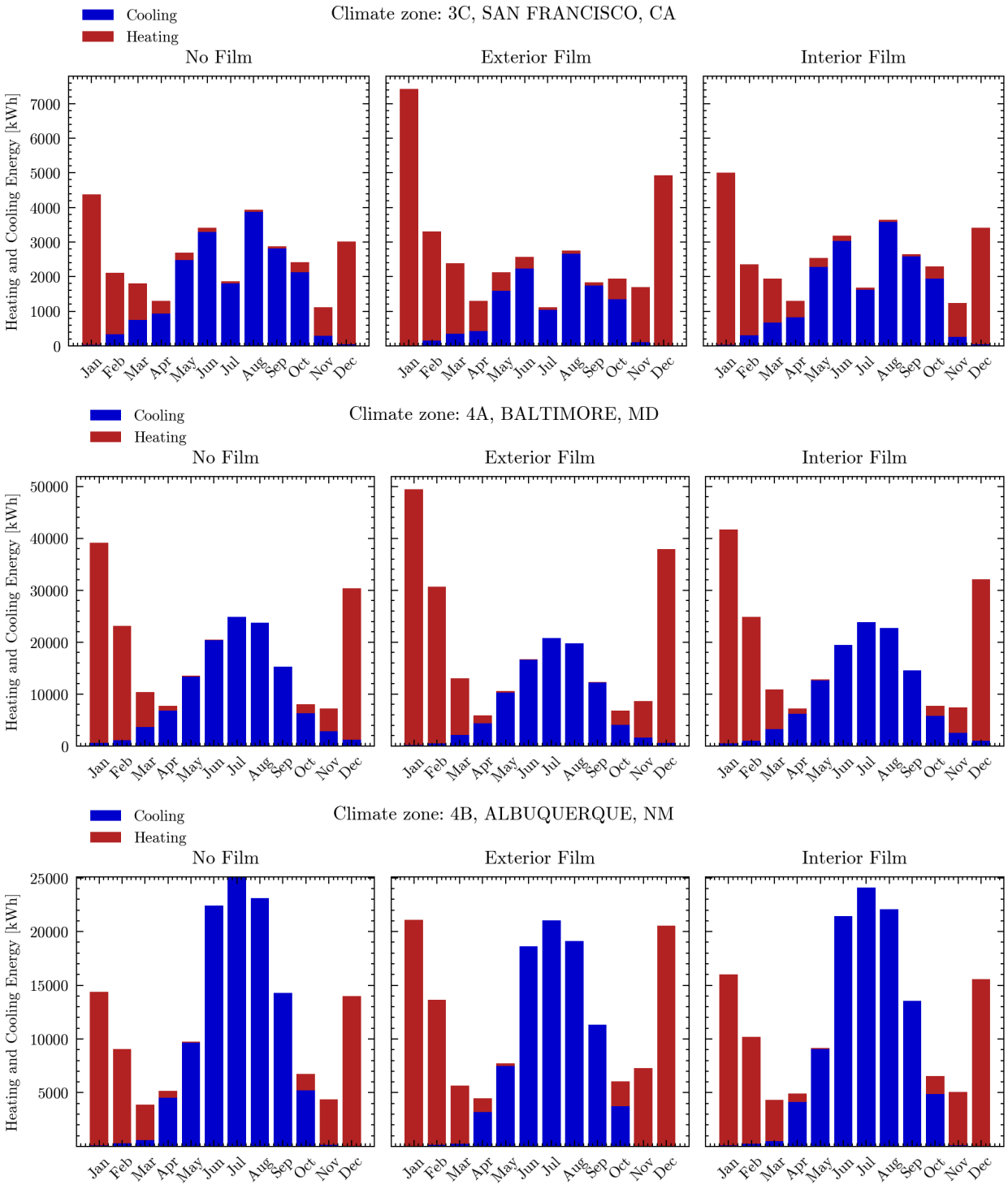
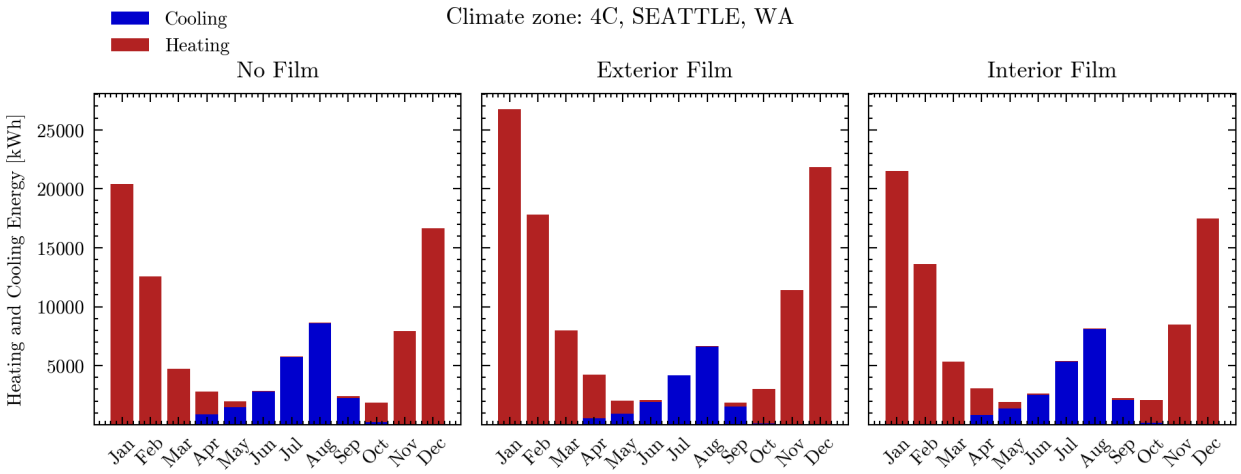


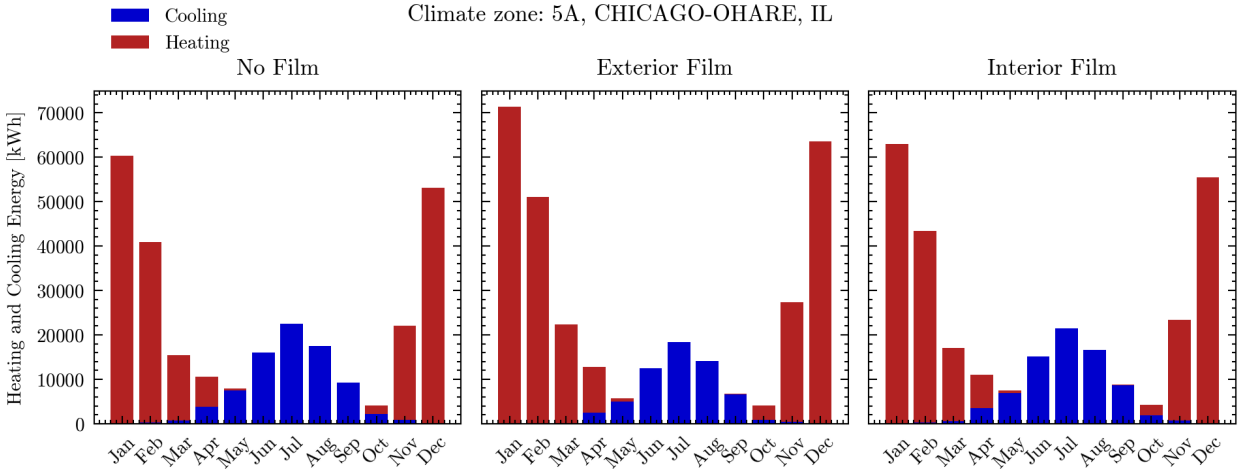
Figure A7: Energy cost savings by ASHRAE climate zones: double clear bronze window with film applied on the interior.

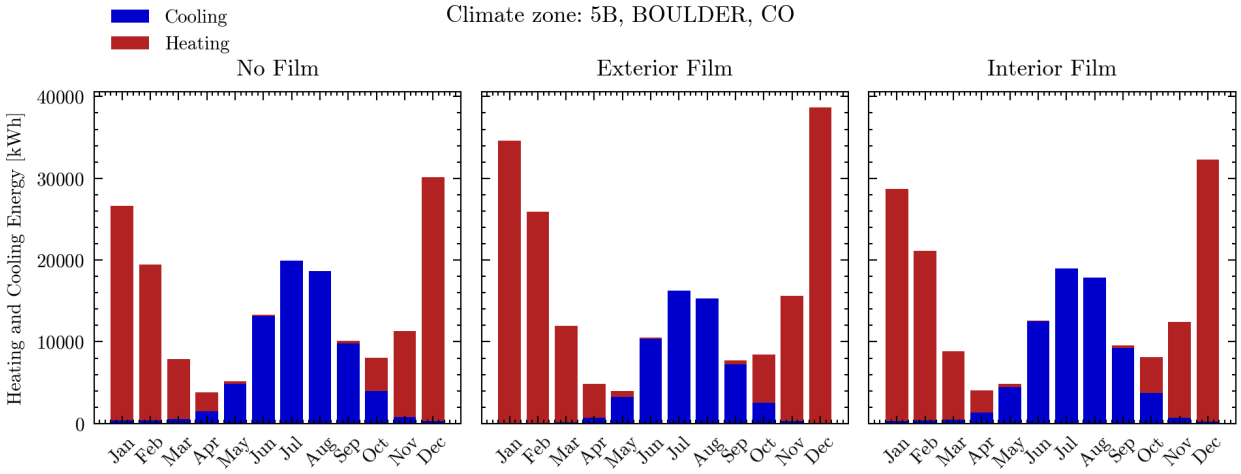

Cooling
Heating
Climate zone: 1A, MIAMI, FL
No Film
Exterior Film
Interior Film
Heating and Cooling Energy [kWh]
0
5000
10000
15000
20000
25000
30000
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Cooling
Heating
Climate zone: 2A, HOUSTON, TX
No Film
Exterior Film
Interior Film
Heating and Cooling Energy [kWh]
0
5000
10000
15000
20000
25000
30000
35000
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Cooling
Heating
Climate zone: 2B, PHOENIX, AZ
No Film
Exterior Film
Interior Film
Heating and Cooling Energy [kWh]
0
10000
20000
30000
40000
50000
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

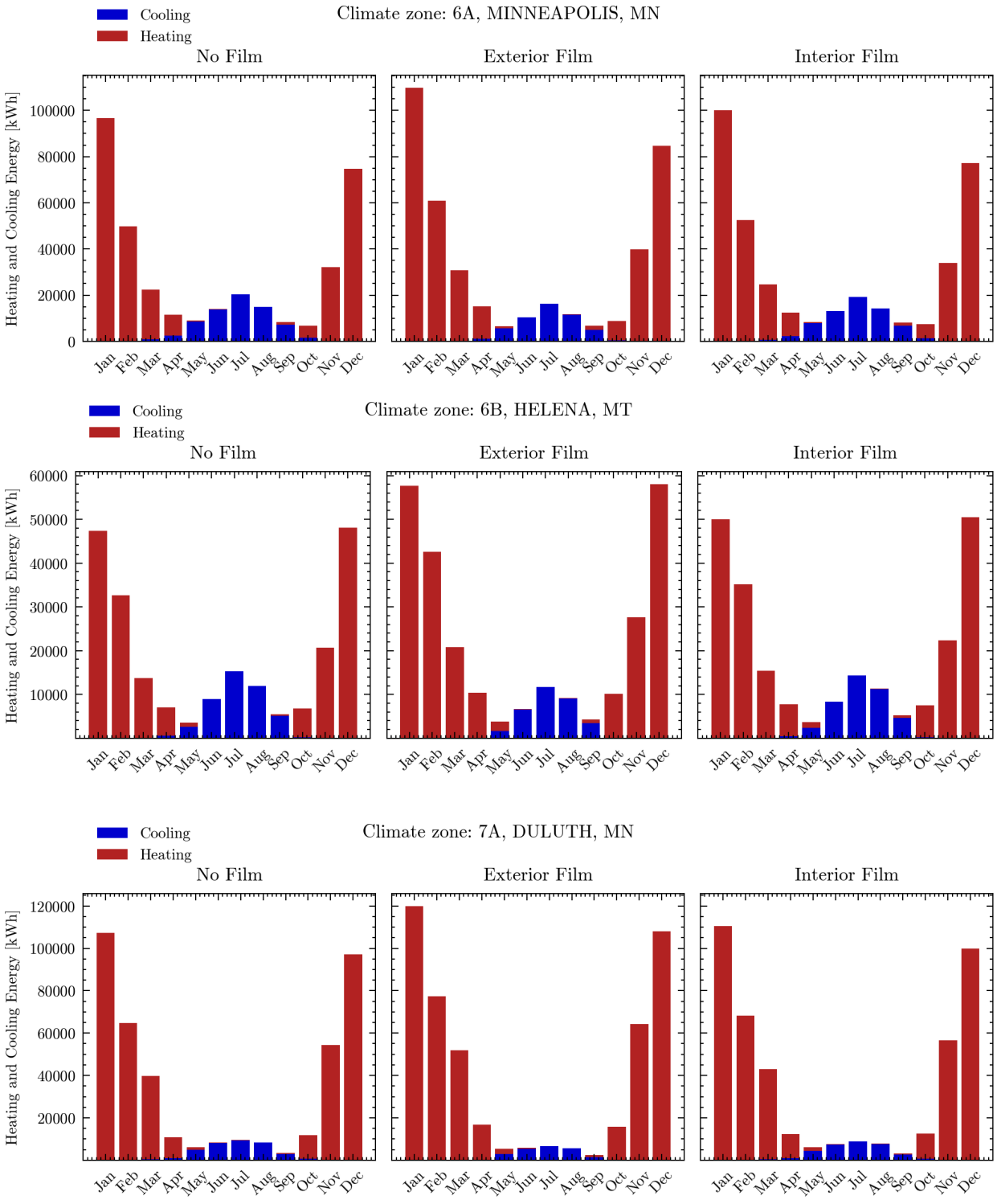

Cooling
Heating
Climate zone: 3A, ATLANTA, GA
No Film
Exterior Film
Interior Film
Heating and Cooling Energy [kWh]
0
5000
10000
15000
20000
25000
30000
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Cooling
Heating
Climate zone: 3B, LAS VEGAS, NV
No Film
Exterior Film
Interior Film
Heating and Cooling Energy [kWh]
0
10000
20000
30000
40000
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Cooling
Heating
Climate zone: 3B, LOS ANGELES, CA
No Film
Exterior Film
Interior Film
Heating and Cooling Energy [kWh]
0
2000
4000
6000
8000
10000
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Cooling
Heating
Climate zone: 3C, SAN FRANCISCO, CA
No Film
Exterior Film
Interior Film
Heating and Cooling Energy [kWh]
0
1000
2000
3000
4000
5000
6000
7000
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Cooling
Heating
Climate zone: 4A, BALTIMORE, MD
No Film
Exterior Film
Interior Film
Heating and Cooling Energy [kWh]
0
10000
20000
30000
40000
50000
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Cooling
Heating
Climate zone: 4B, ALBUQUERQUE, NM
No Film
Exterior Film
Interior Film
Heating and Cooling Energy [kWh]
5000
10000
15000
20000
25000
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Cooling
Heating
Climate zone: 4C, SEATTLE, WA
No Film
Exterior Film
Interior Film
Heating and Cooling Energy [kWh]
25000
20000
15000
10000
5000
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Cooling
Heating
Climate zone: 5A, CHICAGO-OHARE, IL
No Film
Exterior Film
Interior Film
Heating and Cooling Energy [kWh]
70000
60000
50000
40000
30000
20000
10000
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Cooling
Heating
Climate zone: 5B, BOULDER, CO
No Film
Exterior Film
Interior Film
Heating and Cooling Energy [kWh]
40000
30000
20000
10000
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Climate zone: 6A, MINNEAPOLIS, MN
Cooling
Heating
No Film
Exterior Film
Interior Film
Heating and Cooling Energy [kWh]
0
20000
40000
60000
80000
100000
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Climate zone: 6B, HELENA, MT
Cooling
Heating
No Film
Exterior Film
Interior Film
Heating and Cooling Energy [kWh]
10000
20000
30000
40000
50000
60000
Climate zone: 7A, DULUTH, MN
Cooling
Heating
No Film
Exterior Film
Interior Film
Heating and Cooling Energy [kWh]
20000
40000
60000
80000
100000
120000

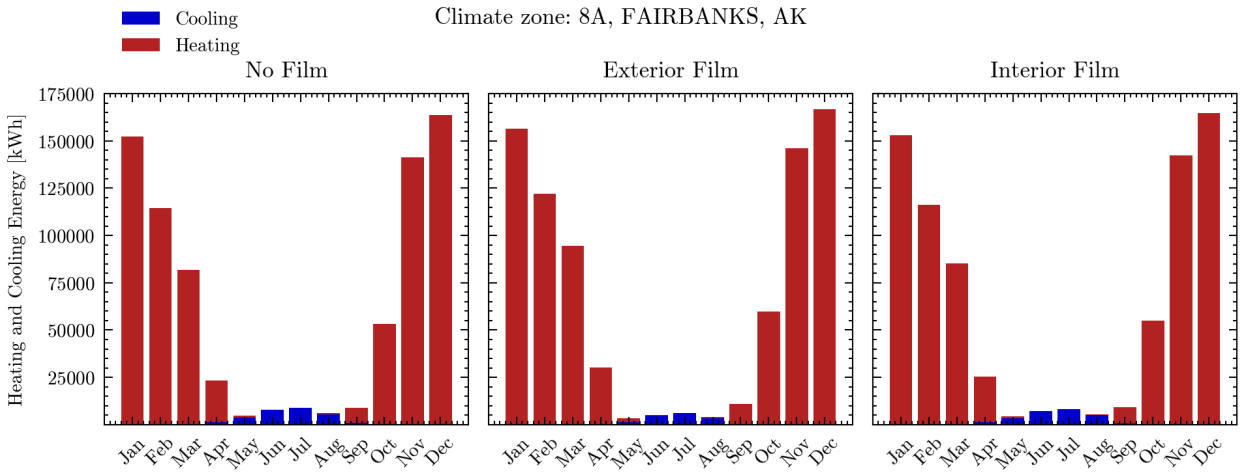
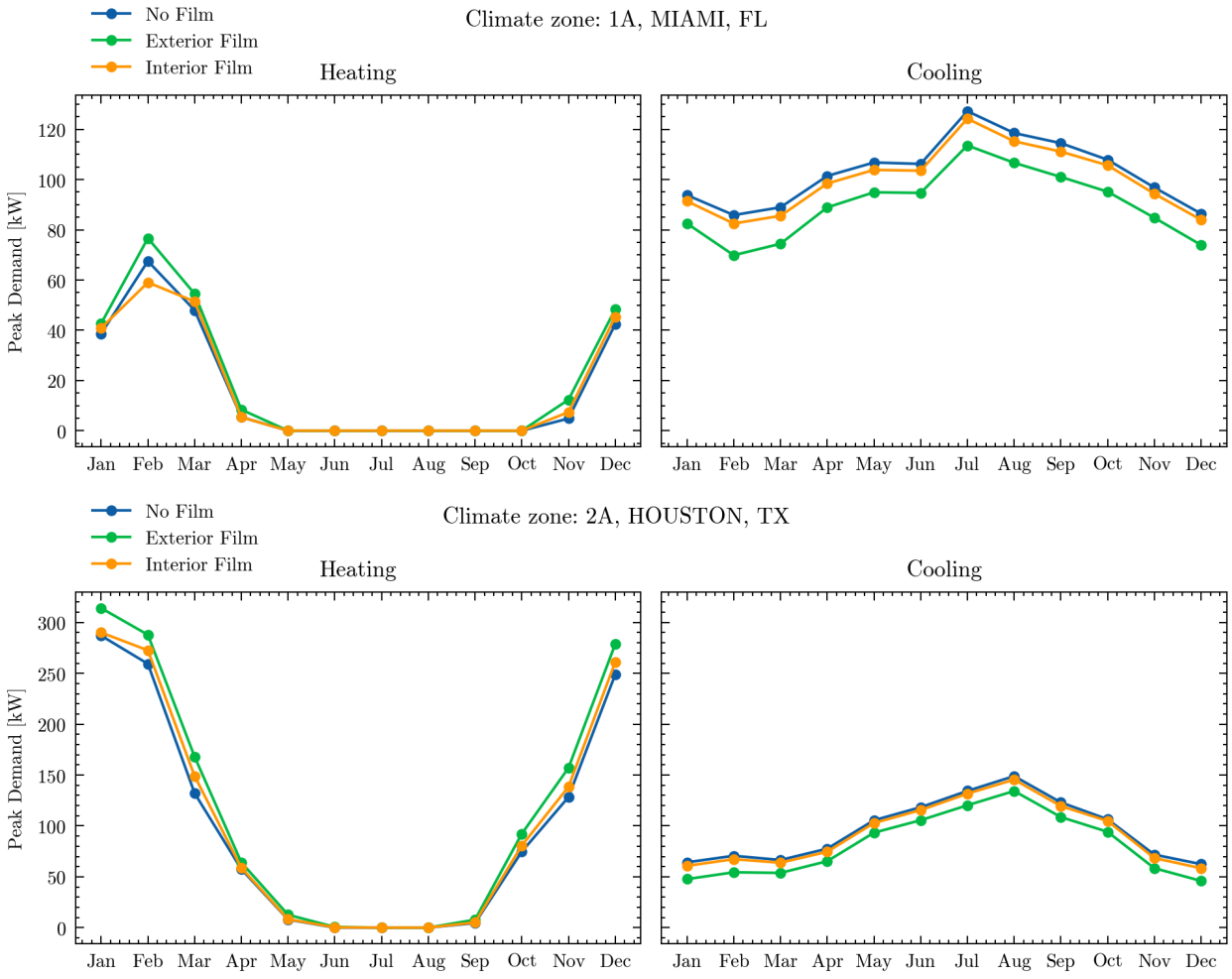
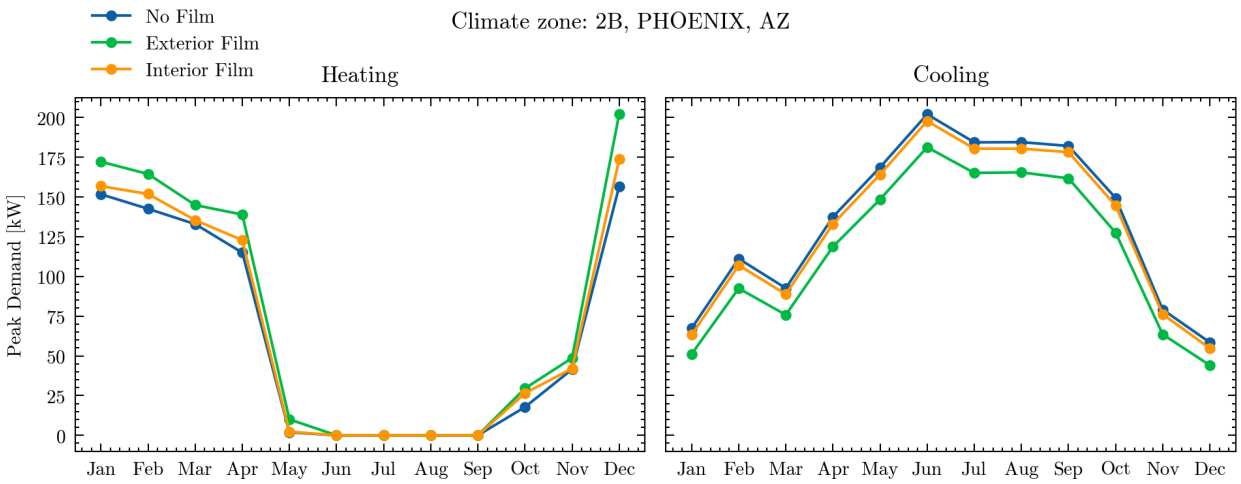
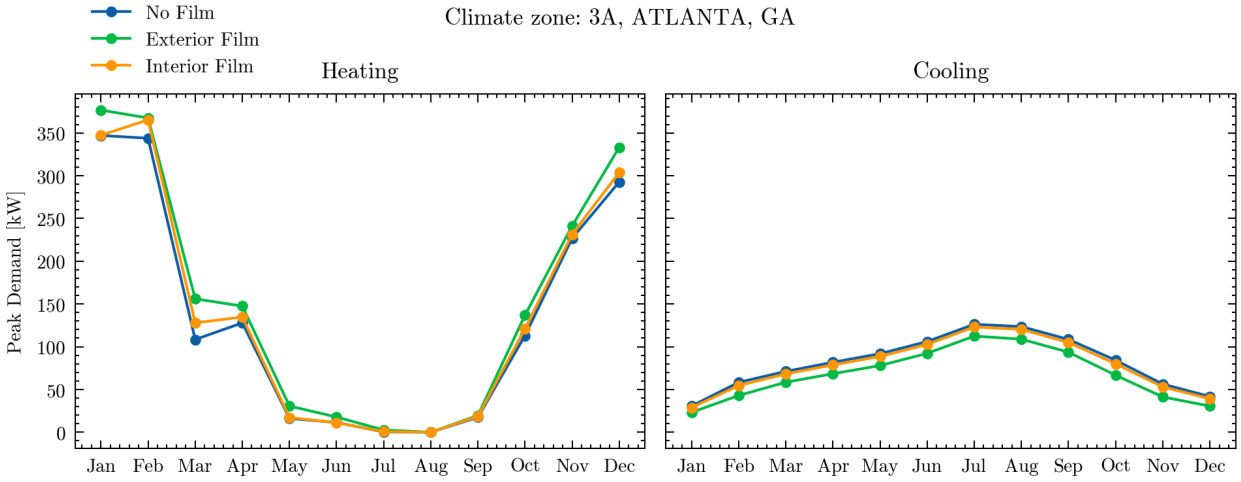
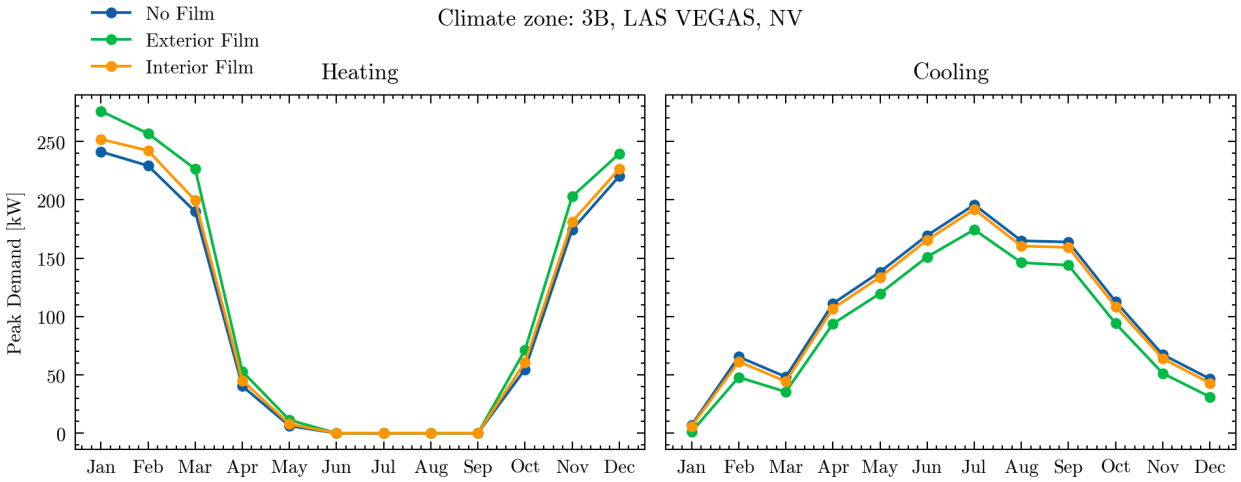


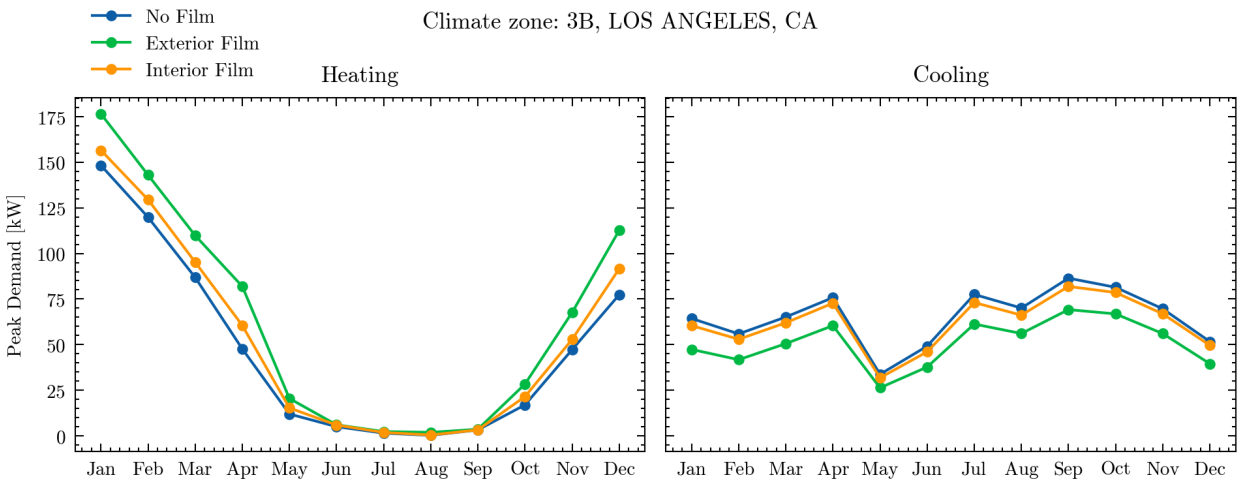
Figure A8. Simulated heating and cooling energy use between the base case and exterior and interior film retrofit for all ASHRAE climate zones.

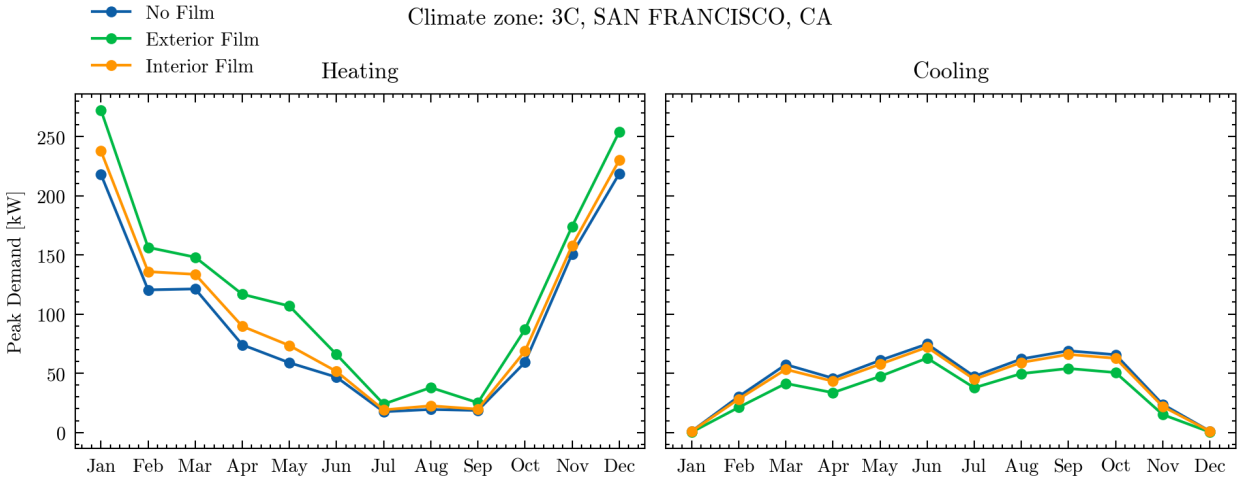


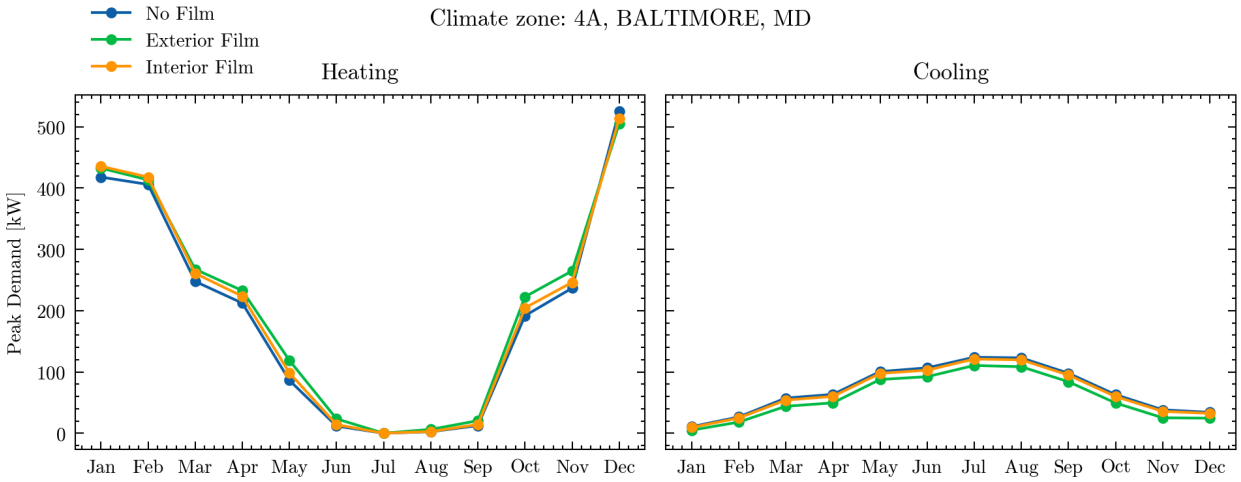

No Film
Exterior Film
Interior Film
Climate zone: 2B, PHOENIX, AZ
Heating
Cooling
Peak Demand [kW]
0
25
50
75
100
125
150
175
200
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

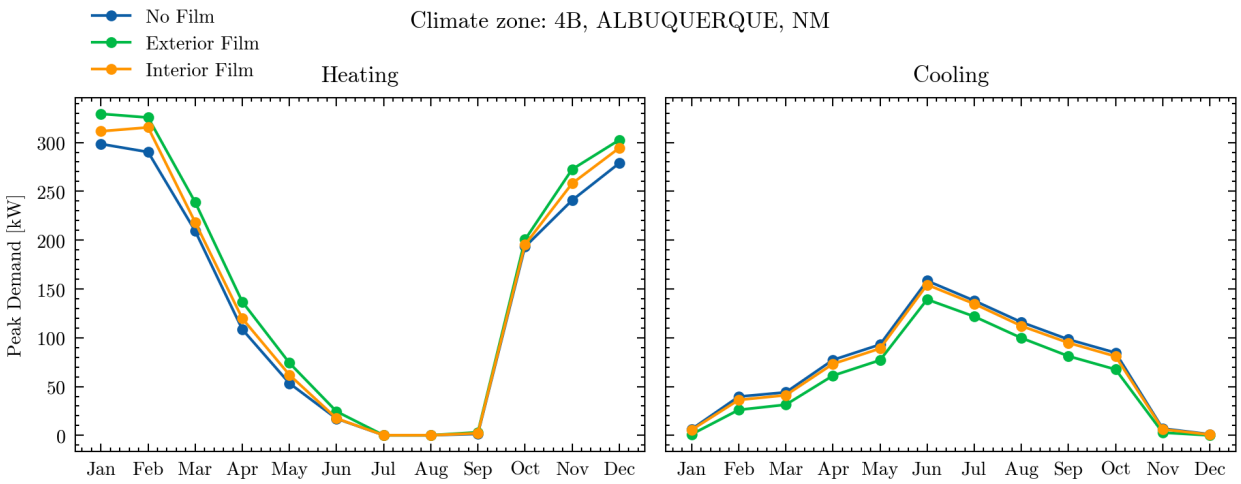

No Film
Exterior Film
Interior Film
Climate zone: 3A, ATLANTA, GA
Heating
Cooling
Peak Demand [kW]
0
50
100
150
200
250
300
350
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

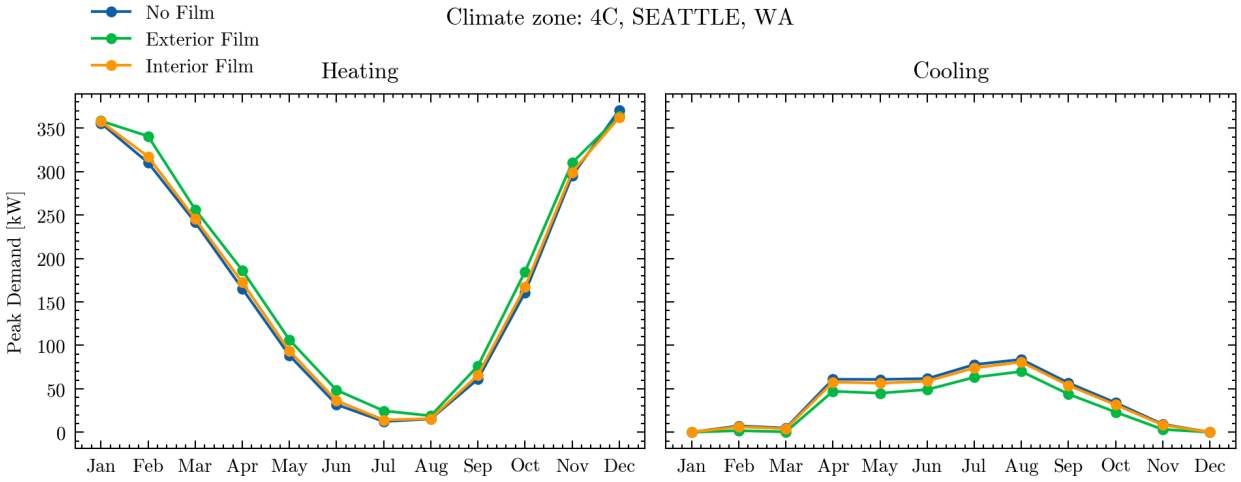

No Film
Exterior Film
Interior Film
Climate zone: 3B, LAS VEGAS, NV
Heating
Cooling
Peak Demand [kW]
0
50
100
150
200
250
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

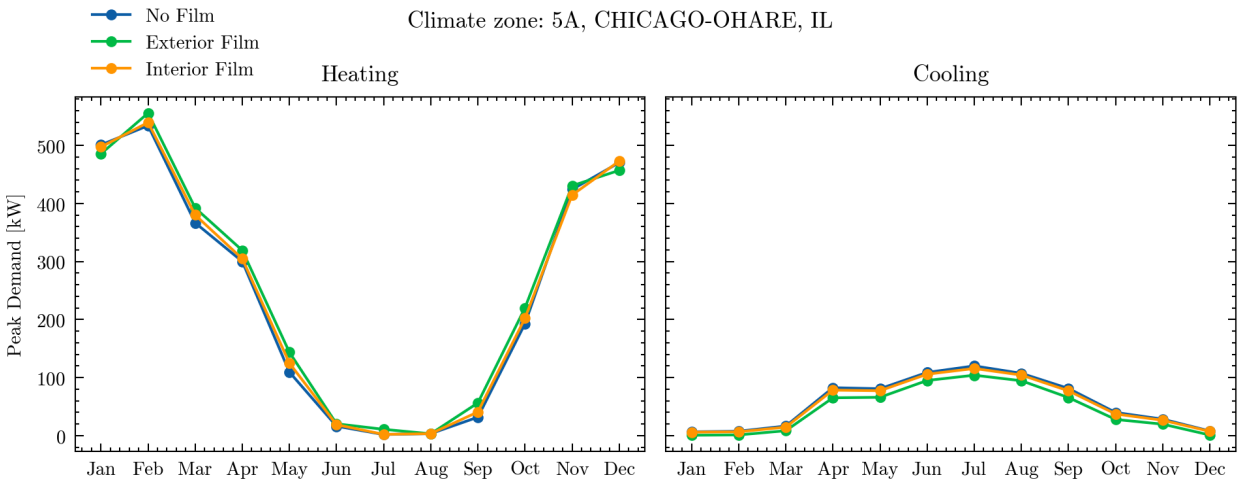

No Film
Exterior Film
Interior Film
Climate zone: 3B, LOS ANGELES, CA
Heating
Cooling
Peak Demand [kW]
0
25
50
75
100
125
150
175
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

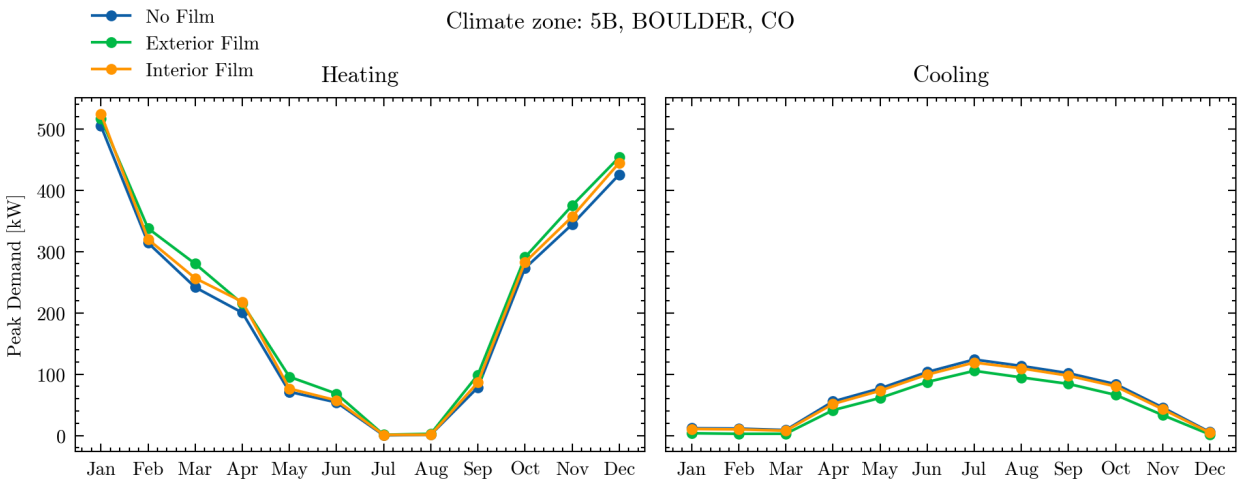

No Film
Exterior Film
Interior Film
Climate zone: 3C, SAN FRANCISCO, CA
Heating
Cooling
Peak Demand [kW]
0
50
100
150
200
250
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

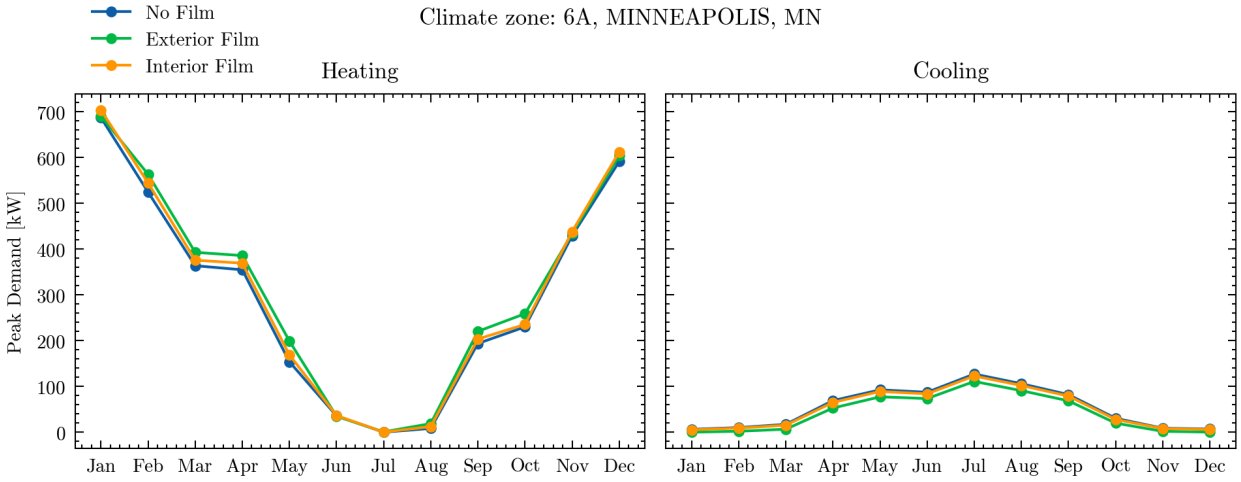

No Film
Exterior Film
Interior Film
Climate zone: 4A, BALTIMORE, MD
Heating
Cooling
Peak Demand [kW]
0
100
200
300
400
500
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

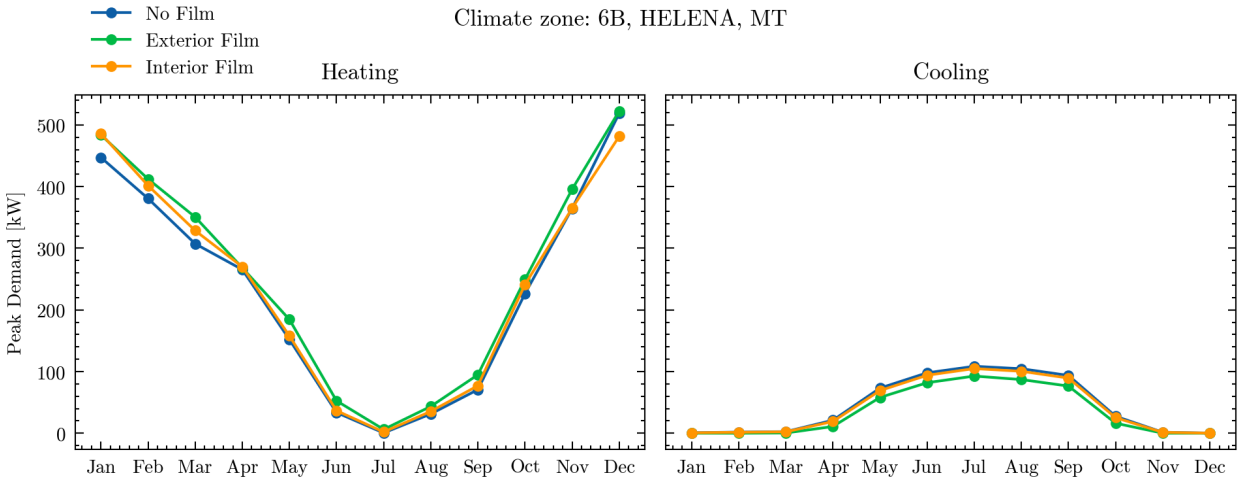

No Film
Exterior Film
Interior Film
Climate zone: 4B, ALBUQUERQUE, NM
Heating
Cooling
Peak Demand [kW]
0
50
100
150
200
250
300
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec


No Film
Exterior Film
Interior Film
Climate zone: 4C, SEATTLE, WA
Heating
Cooling
Peak Demand [kW]
0
50
100
150
200
250
300
350
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec


No Film
Exterior Film
Interior Film
Climate zone: 5A, CHICAGO-OHARE, IL
Heating
Cooling
Peak Demand [kW]
0
100
200
300
400
500
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec


No Film
Exterior Film
Interior Film
Climate zone: 5B, BOULDER, CO
Heating
Cooling
Peak Demand [kW]
0
100
200
300
400
500
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec


No Film
Exterior Film
Interior Film
Climate zone: 6A, MINNEAPOLIS, MN
Heating
Cooling
Peak Demand [kW]
0
100
200
300
400
500
600
700
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec


No Film
Exterior Film
Interior Film
Climate zone: 6B, HELENA, MT
Heating
Cooling
Peak Demand [kW]
0
100
200
300
400
500
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

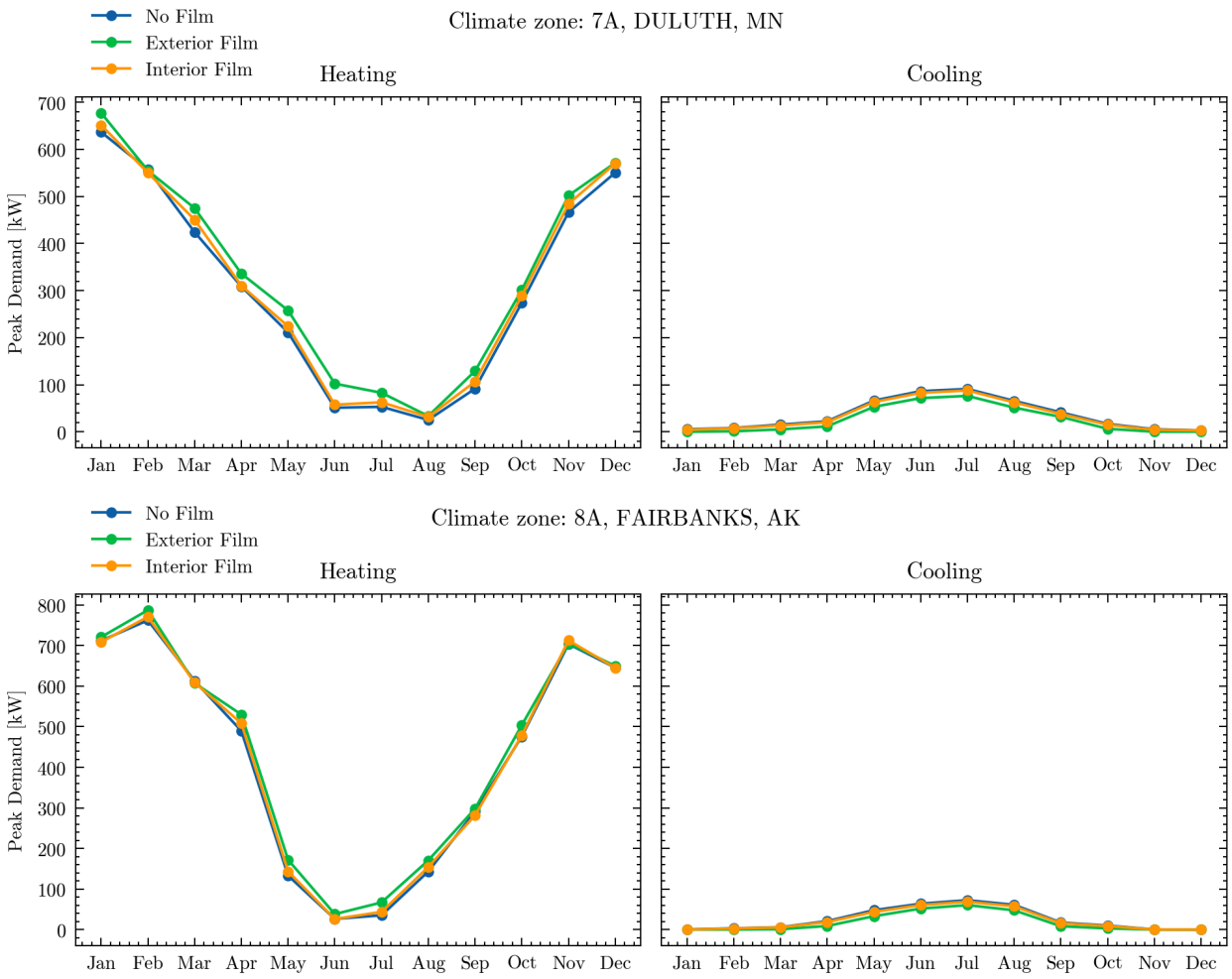


Figure A9. Simulated monthly peak heating and cooling power between the base case and exterior and interior film retrofit for all ASHRAE climate zones.

Energy simulation (Building 67 specific model)

More detailed simulations were attempted in order to quantify the magnitude of energy savings at Building 67, using data about the building's characteristics and energy consumption prior to the film retrofit. The model features a gross floor area of 373,000 square feet, a 47% Window-to Wall Ratio (WWR), and employs a VAV HVAC system with a chiller for cooling and a natural gas boiler for heating. Due to its high complexity, Building 67's unique perimeter heating and cooling system, some details of which were not known to the study team at the beginning of the study, was not modeled, and the building was modeled as if it was heated and cooled by a conventional VAV system only. The perimeter system operates in addition to the conventional, ceiling-mounted VAV system, and includes:

- Radiators that run the perimeter of each floor, below the windows. These radiators run hot or cold water, depending on the season.

- Air ducts encased in concrete columns along the facade. The air in these ducts is directed around the radiators before entering the conditioned space, adding to the heating/cooling. Air is supplied by air handling units (AHUs) on every fourth floor. Each AHU supplies air to four floors.

Further information about this system was difficult to obtain, beyond the original drawings shown in Figure A10.

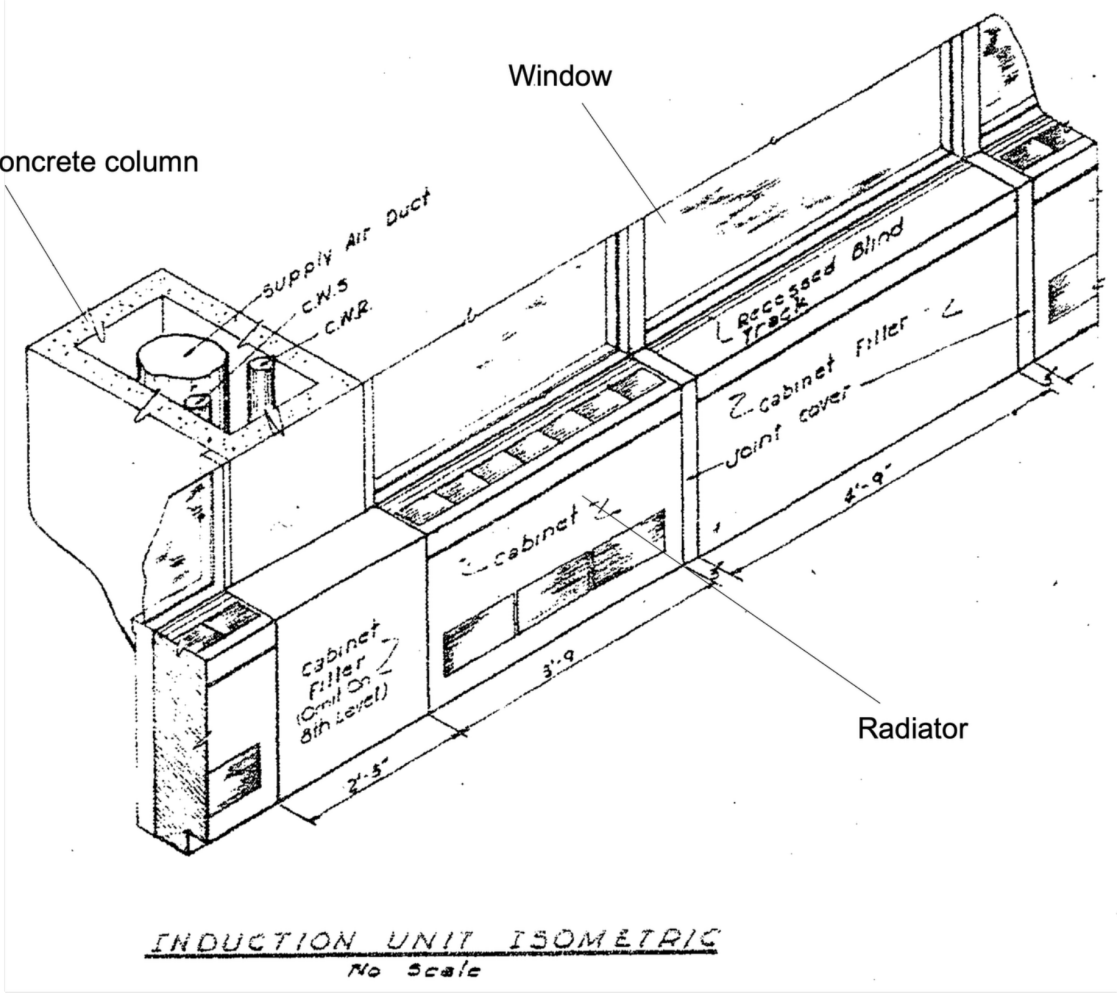


Figure A10. Detail of original building drawings showing the perimeter of the HVAC system.

The heating penalties shown below in the results for these simulations are unusual and out of line with what would be expected for a building like Building 67. This may be related to not being able to accurately model the behavior of the HVAC system due to the inherent challenges in modeling such a unique system. While developing an accurate model of such a unique system was outside the scope of this project, the modeling assumptions, process, and results are included in this appendix for completeness.

Two primary simulation models were developed. The first one is a model of Building 67 and uses building information with 2023 Denver weather data. The second model was developed for other ASHRAE climate zones with significant cooling needs. It adapts the GSA Building 67 model for three different ASHRAE

climate zones—Miami, FL (climate zone 1A); Houston, TX (climate zone 2A); and Phoenix, AZ (climate zone 2B)—using TMY3 weather data. For this adaptation, the building envelope is modified to a pre-1980 condition typical for the respective ASHRAE climate zone, and the baseline HVAC system is sized to each ASHRAE climate zone. All film simulations maintain identical chiller and boiler capacities. The energy model was initially created in DesignBuilder and subsequently converted to EnergyPlus.

The energy performance analysis for this energy simulation was carried out in three main phases.

Energy model tuning

This step involves tuning the building simulation model, with the baseline window configuration, using building's measured energy data for 2023. Metrics for tuning include total site electricity consumption, natural gas consumption, and total site energy consumption.

The tuned building energy model was assessed against measured data for three key performance objectives using the Normalized Mean Bias Error (NMBE) and Coefficient of Variation of Root Mean Square Error (CVRMSE) metrics. Annual electricity consumption (Measured: 3,481,504 kWh; Simulated: 3,564,751 kWh) showed NMBE: 2.4% and CVRMSE: 10.8%. Annual natural gas consumption (Measured: 3,053,134 kWh; Simulated: 3,107,741 kWh) achieved NMBE: 1.8% and CVRMSE: 9.6%. Total annual site energy consumption (Measured: 6,534,638 kWh; Simulated: 6,672,492 kWh) resulted in NMBE: 2.1% and CVRMSE: 7.8%. Positive NMBE indicates slight simulation over-prediction, while low CVRMSE confirms good fit for variability.

Table A2. Energy model tuning summary.

Performance objective	Measured site energy use	Tuned baseline simulated energy use	Tuned simulation accuracy (NMBE/CVRMSE)
Annual electricity consumption	3,481,504 kWh	3,564,751 kWh	NMBE: 2.4% CVRMSE: 10.8%
Annual natural gas consumption	3,053,134 kWh	3,107,741 kWh	NMBE: 1.8% CVRMSE: 9.6%
Annual site energy consumption	6,534,638 kWh	6,672,492 kWh	NMBE: 2.1% CVRMSE: 7.8%

Comparison of energy performance between baseline and film in Denver

This phase compares the simulated energy performance of the Building 67 model with a baseline window configuration to the same model after applying a window film to the south, east, and west facing windows. The comparison focuses on HVAC electricity and natural gas consumption, and HVAC peak electricity demand. Both window configurations have an identical U-value (0.333 Btu/h·ft2·°F). The film significantly changes the properties of the windows, reducing the Solar Heat Gain Coefficient (SHGC) from the baseline of 0.333 to 0.173, and the Visible Transmittance (VT) from 0.451 to 0.210.

For annual HVAC electricity energy consumption, the film results in reductions across all components: cooling energy from 431,326 kWh/yr to 424,104 kWh/yr (a difference of 7,222 kWh/yr), fan energy from 1,028,429 kWh/yr to 985,394 kWh/yr (a difference of 43,034 kWh/yr), pump energy from 18,561 kWh/yr to 18,493 kWh/yr (a difference of 68 kWh/yr), and cooling tower energy from 117,454 kWh/yr to 116,750 kWh/yr (a difference of 704 kWh/yr). The total annual HVAC electricity consumption was reduced from 1,595,789 kWh/yr to 1,544,762 kWh/yr (a savings of 51,027 kWh/yr), but gas consumption increased from 3,107,741 kWh/yr to 3,311,814 kWh/yr (an increase of 204,073 kWh/yr). The monthly HVAC peak electricity demand range for the 3M film (117 - 319 kW) is lower than the baseline (122 - 335 kW), showing a reduction of 1.7% to 4.7%.

Table A3. Energy performance summary of the base line and film in Denver.

Performance objective	Baseline simulation	Film simulation	Difference
Annual HVAC electricity consumption	Cooling: 431,326 kWh/yr Fan: 1,028,429 kWh/yr Pump: 18,561 kWh/yr Cooling Tower: 117,454 kWh/yr	Cooling: 424,104 kWh/yr Fan: 985,394 kWh/yr Pump: 18,493 kWh/yr Cooling Tower: 116,750 kWh/yr	Cooling: 1.7% Fan: 4.2% Pump: 0.4% Cooling Tower: 0.6%
Annual HVAC consumption	Electricity: 1,595,789 kWh/yGas: 3,107,741 kWh/yr	Electricity: 1,544,762 kWh/yr Gas: 3,311,814 kWh/yr	Electricity: 3.2% Gas: -6.6%
Monthly HVAC peak electricity demand	122 - 335 kW	117 - 319 kW	1.7% - 4.7%

Comparison of energy performance between baseline and film in other ASHRAE climate zones (Miami, Houston and Phoenix)

This phase compares the energy performance of the baseline and the film application using the Building 67 model that was adapted for three ASHRAE climate zones where the film is expected to perform the best: 1A (Miami, FL), 2A (Houston, TX), and 2B (Phoenix, AZ).

Simulation results show that the film resulted in a significant reduction in total annual HVAC electricity consumption for all zones, Miami FL saving the greatest amount (81,020 kWh/yr), Houston, TX (2A) showed the next highest savings (67,542 kWh/yr), and Phoenix AZ (2B) saving the least amount (59,496 kWh/yr). Annual HVAC electricity energy consumption reduction was primarily due to reductions in cooling energy (49,012 kWh/yr in 1A, 37,205 kWh/yr in 2A, and 23,990 kWh/yr in 2B). Following cooling, significant savings were also attributed to reduced fan electricity consumption, which decreased by 31,047 kWh/yr in Miami (1A), 29,275 kWh/yr in Houston (2A), and 34,409 kWh/yr in Phoenix (2B). Further components of the electricity savings include minor reductions in pump energy consumption, which were 420 kWh/yr in Miami (1A), 318 kWh/yr in Houston (2A), and 260 kWh/yr in Phoenix (2B) and cooling tower differences were 542 kWh/yr (1A), 744 kWh/yr (2A), and 838 kWh/yr (2B). Annual HVAC gas consumption saw increases of 6,402 kWh/yr (1A), 71,296 kWh/yr (2A), and 85,291 kWh/yr (2B). Monthly HVAC peak electricity demand showed a difference in the percentage range of 2.7 - 4.7% in 1A, 1.0 - 4.1% in 2A and 1.0 - 4.5% in 2B.

Table A4. Energy performance summary of the base line and film in other ASHRAE climate zones.

Performance objective	Baseline simulation	Film simulation	Difference
Annual HVAC electricity consumption: Cooling	1A: 1,845,234 kWh/yr 2A: 1,451,135 kWh/yr 2B: 1,242,668 kWh/yr	1A: 1,796,222 kWh/yr 2A:1,413,929 kWh/yr 2B: 1,218,677 kWh/yr	1A: 2.7% 2A: 2.6% 2B: 1.9%
Annual HVAC electricity consumption: Fan	1A: 777,841 kWh/yr 2A: 821,730 kWh/yr 2B: 980,769 kWh/yr	1A: 746,795 kWh/yr 2A: 792,455 kWh/yr 2B: 946,361 kWh/yr	1A: 4.0% 2A: 3.6% 2B: 3.5%
Annual HVAC electricity consumption: Pump	1A: 54,125 kWh/yr 2A: 44,730 kWh/yr 2B: 43,712 kWh/yr	1A: 53,705 kWh/yr 2A: 44,412 kWh/yr 2B: 43,452 kWh/yr	1A: 0.8% 2A: 0.7% 2B: 0.6%

Performance objective	Baseline simulation	Film simulation	Difference
Annual HVAC electricity consumption: Cooling Tower	1A: 371,485 kWh/yr 2A: 295,011 kWh/yr 2B: 291,174 kWh/yr	1A: 370,943 kWh/yr 2A: 295,011 kWh/yr 2B: 290,336 kWh/yr	1A: 0.1% 2A: 0.3% 2B: 0.3%
Annual HVAC energy consumption: Electricity	1A: 3,048,686 kWh/yr 2A: 2,612,613 kWh/yr 2B: 2,558,329 kWh/yr	1A: 2,967,666 kWh/yr 2A: 2,545,072 kWh/yr 2B: 2,498,833 kWh/yr	1A: 2.7% 2A: 2.6% 2B: 2.3%
Annual HVAC energy consumption: Gas	1A: 50,946 kWh/yr 2A: 923,469 kWh/yr 2B :537,064 kWh/yr	1A: 57,348 kWh/yr 2A: 994,765 kWh/yr 2B: 622,355 kWh/yr	1A: -12.6% 2A: -7.7% 2B: -15.9%
Monthly HVAC peak electricity demand	1A: 363-492 kW 2A: 315 -531 kW 2B: 322-562 kW	1A: 351-470 kW 2A: 312 -514 kW 2B: 319-544 kW	1A: 2.7 - 4.7% 2A: 1.0 - 4.1% 2B: 1.1 - 4.5%

Table A5. Monthly electricity tuning results between the 2023 measured electricity consumption and 2023 baseline simulated electricity consumption for Building 67 in Denver, CO.

Month	2023 Measured Electricity [kWh]	2023 Baseline Simulated Electricity [kWh]
1	295,223	286,074
2	283,733	251,826
3	310,951	292,685
4	290,381	253,195
5	310,328	294,359
6	297,150	314,241
7	313,492	351,295
8	302,906	365,822
9	271,910	316,460
10	270,749	300,769
11	268,640	265,085
12	266,041	272,939
Annual	**3,481,504**	**3,564,751**

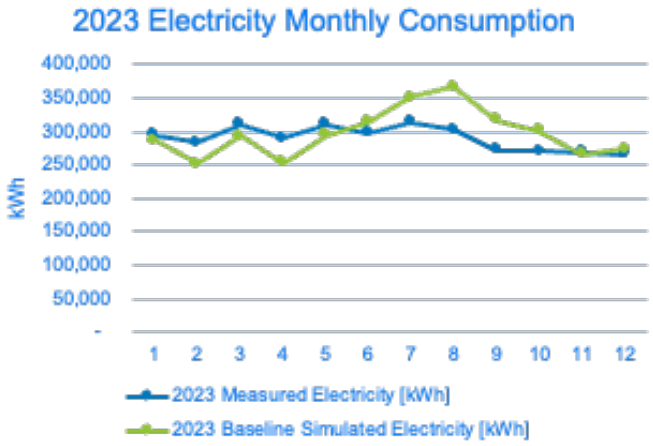


Figure A11. Monthly electricity tuning results between the 2023 measured electricity consumption and 2023 baseline simulated electricity consumption for Building 67 in Denver, CO.

Table A6. Monthly natural gas tuning results between the 2023 measured natural gas consumption and 2023 baseline simulated natural gas consumption for Building 67 in Denver, CO.

Month	2023 Measured Natural Gas [kWh]	2023 Baseline Simulated Natural Gas [kWh]
1	538,546	576,363
2	498,204	514,254
3	492,126	508,148
4	366,890	333,853
5	202,010	154,957
6	317	7
7	2,201	0
8	407	0
9	752	9
10	192,641	222,246
11	356,860	386,251
12	266,041	272,939
Annual	**3,481,504**	**3,564,751**

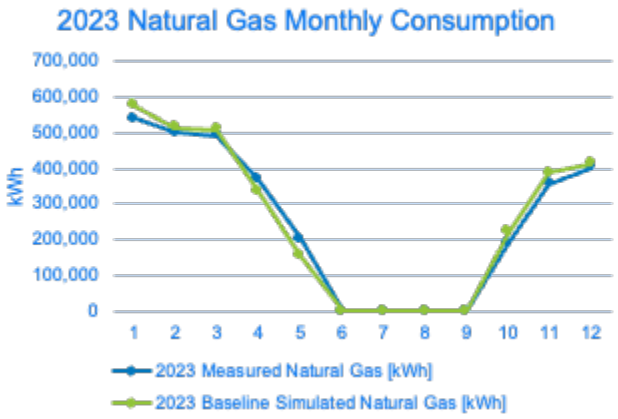


Figure A12. Monthly natural gas tuning results between the 2023 measured natural gas consumption and 2023 baseline simulated natural gas consumption for Building 67 in Denver, CO.

Table A7. Monthly site energy tuning results between the 2023 measured site energy consumption and 2023 baseline simulated site energy consumption for Building 67 in Denver, CO.

Month	2023 Measured Site Energy [kWh]	2023 Simulated Site Energy [kWh]
1	833,769	862,437
2	781,937	766,081
3	803,077	800,833
4	657,271	587,048
5	512,338	449,315
6	297,466	314,248
7	315,693	351,295
8	303,312	365,822
9	272,663	316,469
10	463,390	523,016
11	625,500	651,337
12	668,220	684,591
Annual	**6,534,638**	**6,672,492**

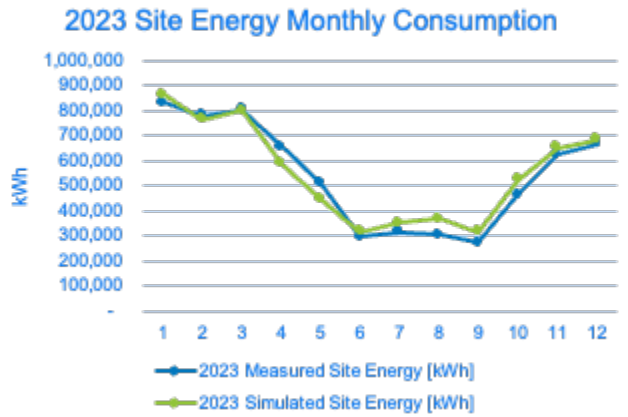


Figure A13. Monthly site energy tuning results between the 2023 measured site energy consumption and 2023 baseline simulated site energy consumption for Building 67 in Denver, CO.

Table A8. Effect of film on HVAC electricity performance: simulated cooling electricity [kWh].

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	282	270	12	4.2%
2	580	556	24	4.2%
3	2,159	2,081	79	3.7%
4	20,557	20,163	394	1.9%
5	40,570	39,896	674	1.7%
6	59,531	58,554	977	1.6%
7	93,153	91,648	1,505	1.6%
8	93,826	92,365	1,461	1.6%
9	68,531	67,459	1,071	1.6%
10	33,608	33,078	530	1.6%
11	14,240	13,904	336	2.4%
12	4,290	4,130	160	3.7%
Annual	**431,326**	**424,104**	**7,222**	**1.7%**

Table A9. Effect of film on HVAC electricity performance: simulated fan electricity [kWh].

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	282	270	12	4.2%
2	580	556	24	4.2%
3	2,159	2,081	79	3.7%
4	20,557	20,163	394	1.9%
5	40,570	39,896	674	1.7%
6	59,531	58,554	977	1.6%
7	93,153	91,648	1,505	1.6%
8	93,826	92,365	1,461	1.6%
9	68,531	67,459	1,071	1.6%
10	33,608	33,078	530	1.6%
11	14,240	13,904	336	2.4%
12	4,290	4,130	160	3.7%
Annual	**431,326**	**424,104**	**7,222**	**1.7%**

Table A10. Effect of film on HVAC electricity performance: simulated pump electricity [kWh].

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	282	270	12	4.2%
2	580	556	24	4.2%
3	2,159	2,081	79	3.7%

Month	Baseline	Film	Saving [kWh]	Saving [%]
4	20,557	20,163	394	1.9%
5	40,570	39,896	674	1.7%
6	59,531	58,554	977	1.6%
7	93,153	91,648	1,505	1.6%
8	93,826	92,365	1,461	1.6%
9	68,531	67,459	1,071	1.6%
10	33,608	33,078	530	1.6%
11	14,240	13,904	336	2.4%
12	4,290	4,130	160	3.7%
Annual	**431,326**	**424,104**	**7,222**	**1.7%**

Table A11. Effect of film on HVAC electricity performance: simulated cooling tower electricity [kWh].

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	60	57	3	4.7%
2	68	63	4	6.5%
3	480	469	11	2.4%
4	5,186	5,119	67	1.3%
5	12,259	12,147	112	0.9%
6	17,177	17,047	131	0.8%
7	24,390	24,330	61	0.2%

Month	Baseline	Film	Saving [kWh]	Saving [%]
8	24,905	24,839	66	0.3%
9	19,211	19,105	106	0.6%
10	9,311	9,255	57	0.6%
11	3,506	3,446	60	1.7%
12	900	875	26	2.9%
Annual	**117,454**	**116,750**	**704**	**0.6%**

Table A12. Effect of film on HVAC energy performance: simulated electricity consumption.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	87,811	84,154	3,656	4.2%
2	79,771	76,448	3,323	4.2%
3	90,264	86,524	3,740	4.1%
4	111,299	107,308	3,991	3.6%
5	142,153	137,717	4,435	3.1%
6	163,832	159,183	4,649	2.8%
7	208,293	203,022	5,271	2.5%
8	209,476	204,240	5,236	2.5%
9	175,028	170,302	4,726	2.7%

Month	Baseline	Film	Saving [kWh]	Saving [%]
10	131,792	127,553	4,239	3.2%
11	103,137	99,214	3,923	3.8%
12	92,934	89,096	3,838	4.1%
Annual	**1,595,789**	**1,544,762**	**51,027**	**3.2%**

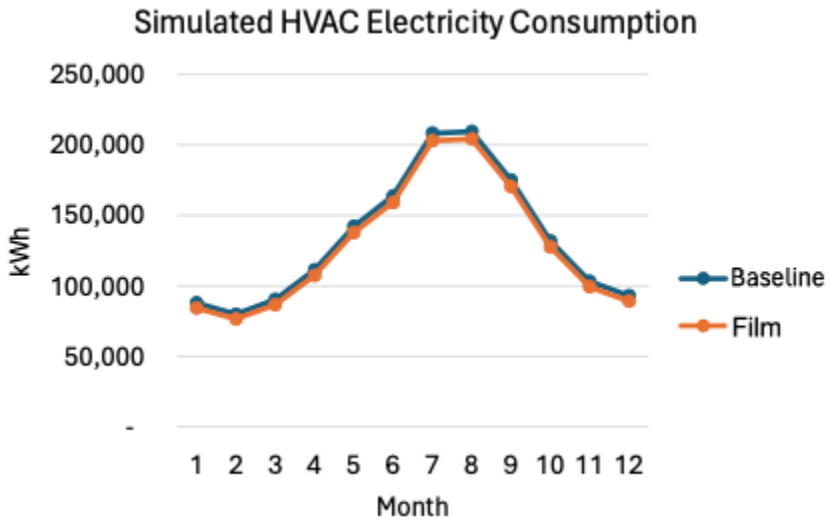


Figure A14. Effect of film on HVAC energy performance: simulated electricity consumption.

Table A13. Effect of film on HVAC energy performance: simulated heating natural gas consumption.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	576,363	604,997	-28,634	-5.0%
2	514,254	547,115	-32,860	-6.4%
3	508,148	535,513	-27,364	-5.4%
4	333,853	354,524	-20,671	-6.2%
5	154,957	169,412	-14,456	-9.3%

Month	Baseline	Film	Saving [kWh]	Saving [%]
6	7	8	-1	N/A
7	0	0	0	N/A
8	0	0	0	N/A
9	9	11	-2	N/A
10	222,246	245,627	-23,381	-10.5%
11	386,251	414,346	-28,095	-7.3%
12	411,651	440,260	-28,609	-6.9%
Annual	**3,107,741**	**3,311,814**	**-204,073**	**-6.6%**

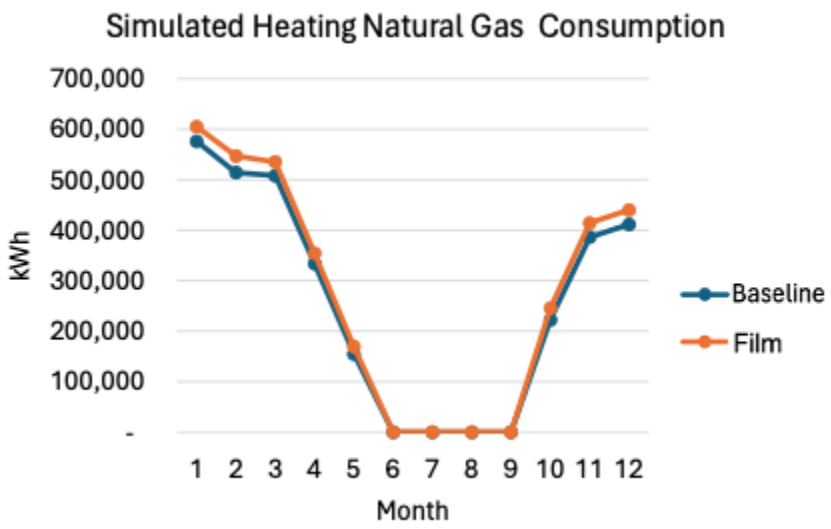


Figure A15. Effect of film on HVAC energy performance: simulated heating natural gas consumption.

Table A14. Effect of film on HVAC peak electricity demand.

Month	Baseline HVAC Peak [kW]	Film HVAC Peak [kW]	Peak Time	Reduction [%]
1	122	117	01/10 13:00	4.0%
2	198	189	02/13 13:00	4.1%
3	285	281	03/15 13:00	1.7%
4	292	285	04/11 17:00	2.4%
5	290	284	05/23 15:00	2.1%
6	308	296	06/27 15:00	3.8%
7	331	319	07/20 17:00	3.7%
8	335	319	08/22 16:00	4.7%
9	325	312	09/01 16:00	3.9%
10	298	289	10/20 15:00	2.8%
11	286	281	11/07 12:00	1.7%
12	286	281	12/06 14:00	1.7%

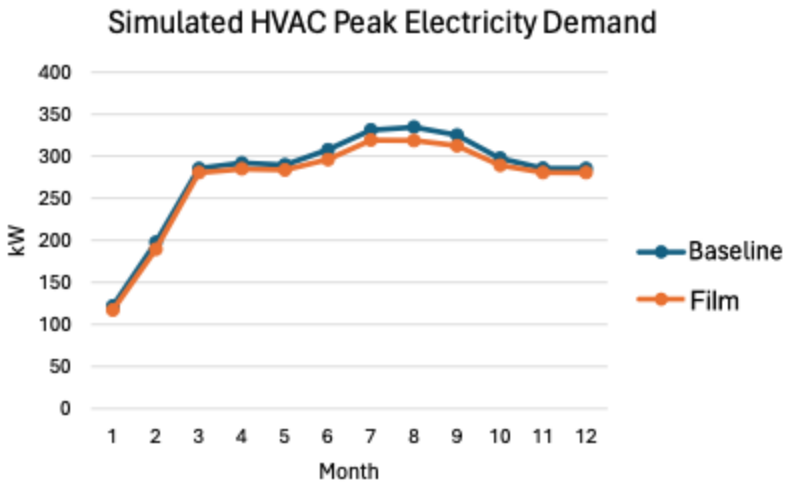


Figure A16. Effect of film on HVAC peak electricity demand.

Table A15. Effect of film on HVAC electricity performance: simulated cooling electricity [kWh] in Miami FL.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	101,551	99,585	1,966	1.9%
2	103,570	101,677	1,893	1.8%
3	123,312	120,569	2,744	2.2%
4	135,938	133,442	2,496	1.8%
5	166,878	162,754	4,125	2.5%
6	187,465	181,774	5,691	3.0%
7	199,543	193,126	6,416	3.2%
8	200,854	194,458	6,397	3.2%
9	186,233	180,471	5,762	3.1%
10	175,840	170,731	5,109	2.9%
11	143,691	140,061	3,630	2.5%
12	120,360	117,576	2,784	2.3%
Annual	**1,845,234**	**1,796,222**	**49,012**	**2.7%**

Table A16. Effect of film on HVAC electricity performance: simulated fan electricity [kWh] in Miami FL.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	65,544	62,999	2,545	3.9%
2	59,219	56,916	2,304	3.9%
3	65,623	63,055	2,568	3.9%
4	63,557	61,069	2,488	3.9%
5	65,999	63,363	2,636	4.0%
6	64,329	61,724	2,605	4.0%
7	66,785	64,064	2,721	4.1%
8	66,750	64,029	2,721	4.1%
9	64,215	61,623	2,592	4.0%
10	66,462	63,727	2,735	4.1%
11	63,757	61,194	2,562	4.0%
12	65,603	63,032	2,571	3.9%
Annual	**777,841**	**746,795**	**31,047**	**4.0%**

Table A17. Effect of film on HVAC electricity performance: simulated pump electricity [kWh] in Miami FL.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	4,041	4,024	17	0.4%
2	3,675	3,657	18	0.5%
3	4,257	4,230	27	0.6%
4	4,386	4,359	27	0.6%
5	4,775	4,738	36	0.8%
6	4,814	4,769	45	0.9%
7	5,017	4,967	50	1.0%
8	5,027	4,978	50	1.0%
9	4,809	4,763	46	1.0%
10	4,846	4,802	44	0.9%
11	4,408	4,375	33	0.8%
12	4,070	4,043	26	0.6%
Annual	**54,125**	**53,705**	**420**	**0.8%**

Table A18. Effect of film on HVAC electricity performance: simulated cooling tower electricity [kWh] in Miami FL.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	26,658	26,477	181	0.7%
2	26,126	26,022	104	0.4%
3	29,310	29,217	93	0.3%
4	31,966	31,946	20	0.1%
5	33,369	33,369	0	0.0%
6	32,292	32,292	0	0.0%
7	33,369	33,369	0	0.0%
8	33,369	33,369	0	0.0%
9	32,292	32,292	0	0.0%
10	33,369	33,369	0	0.0%
11	30,785	30,735	50	0.2%
12	28,581	28,487	94	0.3%
Annual	**371,485**	**370,943**	**542**	**0.1%**

Table A19. Effect of film on HVAC energy performance: simulated electricity consumption in Miami FL.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	197,793	193,085	4,709	2.4%
2	192,591	188,272	4,319	2.2%
3	222,502	217,071	5,432	2.4%
4	235,847	230,815	5,031	2.1%
5	271,020	264,223	6,797	2.5%
6	288,900	280,559	8,341	2.9%
7	304,712	295,525	9,187	3.0%
8	306,000	296,833	9,167	3.0%
9	287,549	279,150	8,399	2.9%
10	280,517	272,629	7,888	2.8%
11	242,640	236,365	6,275	2.6%
12	218,614	213,140	5,475	2.5%
Annual	**3,048,686**	**2,967,666**	**81,020**	**2.7%**

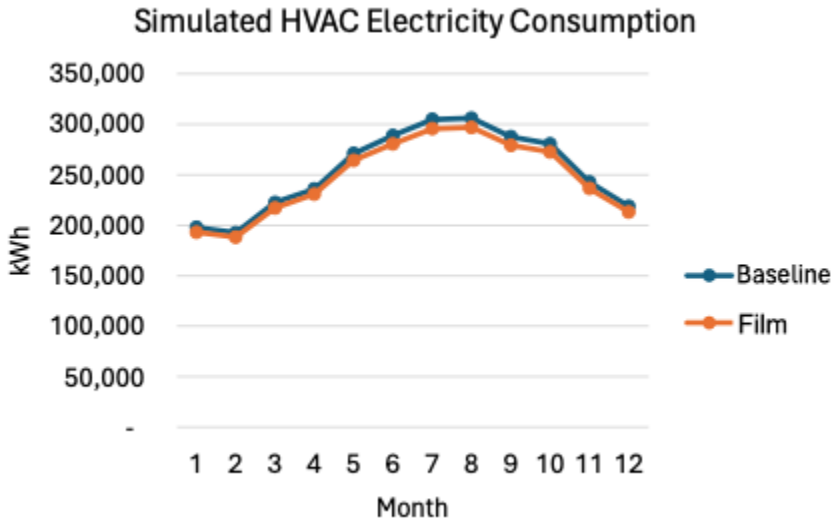


Figure A17. Effect of film on HVAC energy performance: simulated electricity consumption.

Table A20. Effect of film on HVAC energy performance: simulated heating natural gas consumption in Miami FL.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	12,105	13,784	-1,679	-13.9%
2	12,974	14,733	-1,759	-13.6%
3	10,523	11,643	-1,120	-10.6%
4	162	179	-17	-10.3%
5	0	0	0	0.0%
6	0	0	0	0.0%
7	0	0	0	0.0%
8	0	0	0	0.0%
9	0	0	0	0.0%
10	0	0	0	0.0%
11	4,509	4,843	-334	-7.4%
12	10,673	12,167	-1,494	-14.0%
Annual	**50,946**	**57,348**	**-6,402**	**-12.6%**

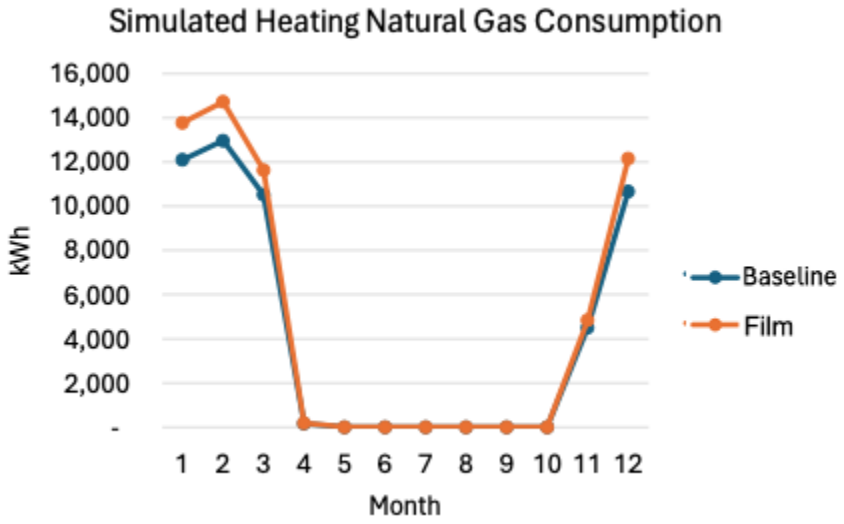


Figure A18. Effect of film on HVAC energy performance: simulated heating natural gas consumption.

Table A21. Effect of film on HVAC peak electricity demand in Miami FL.

Month	Baseline HVAC Peak [kW]	Film HVAC Peak [kW]	Peak Time	Reduction [%]
1	363	351	01/04 10:00	3.3%
2	391	377	02/02 09:00	3.7%
3	395	380	03/10 11:00	3.7%
4	412	397	04/14 15:00	3.7%
5	454	434	05/24 17:00	4.3%
6	460	446	06/08 17:00	3.1%
7	474	459	07/28 16:00	3.3%
8	492	470	08/04 09:00	4.5%
9	466	453	09/22 17:00	2.7%
10	457	442	10/04 11:00	3.3%

Month	Baseline HVAC Peak [kW]	Film HVAC Peak [kW]	Peak Time	Reduction [%]
11	426	409	11/10 15:00	4.0%
12	389	370	12/08 16:00	4.7%

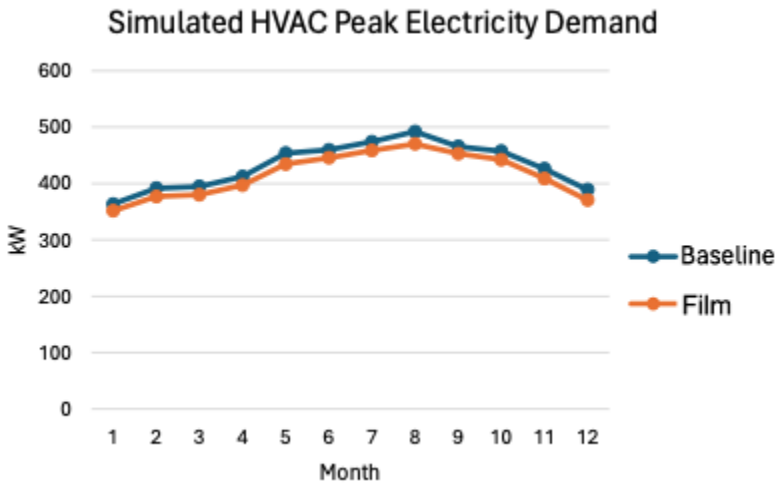


Figure A19. Effect of film on HVAC peak electricity demand.

Table A22. Effect of film on HVAC electricity performance: simulated cooling electricity [kWh] in Houston TX.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	24,624	24,188	436	1.8%
2	47,034	46,470	564	1.2%
3	76,675	75,545	1,130	1.5%
4	114,674	112,564	2,110	1.8%
5	153,080	149,967	3,113	2.0%
6	190,254	184,260	5,994	3.2%
7	210,595	203,558	7,037	3.3%
8	221,000	213,210	7,789	3.5%
9	173,900	168,913	4,988	2.9%
10	110,550	108,745	1,805	1.6%
11	85,193	83,647	1,546	1.8%
12	43,556	42,863	693	1.6%
Annual	**1,451,135**	**1,413,929**	**37,205**	**2.6%**

Table A23. Effect of film on HVAC electricity performance: simulated fan electricity [kWh] in Houston TX.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	69,445	67,016	2,429	3.5%
2	62,724	60,530	2,194	3.5%
3	69,445	67,016	2,429	3.5%
4	67,206	64,855	2,351	3.5%
5	69,522	67,084	2,439	3.5%
6	67,971	65,481	2,489	3.7%
7	70,658	68,019	2,639	3.7%
8	70,852	68,237	2,616	3.7%
9	67,766	65,294	2,472	3.6%
10	69,490	67,052	2,438	3.5%
11	67,207	64,855	2,351	3.5%
12	69,445	67,016	2,429	3.5%
Annual	**821,730**	**792,455**	**29,275**	**3.6%**

Table A24. Effect of film on HVAC electricity performance: simulated pump electricity [kWh] in Houston TX.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	1,628	1,616	12	0.7%
2	2,062	2,059	3	0.1%
3	3,044	3,034	11	0.3%
4	4,046	4,025	21	0.5%
5	4,708	4,678	29	0.6%
6	4,900	4,852	48	1.0%
7	5,168	5,114	54	1.0%
8	5,244	5,187	57	1.1%
9	4,747	4,706	41	0.9%
10	3,922	3,905	18	0.4%
11	3,184	3,169	15	0.5%
12	2,077	2,068	9	0.4%
Annual	**44,730**	**44,412**	**318**	**0.7%**

Table A25. Effect of film on HVAC electricity performance: simulated cooling tower electricity [kWh] in Houston TX.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	7,445	7,330	115	1.5%
2	13,183	13,083	100	0.8%
3	20,145	20,054	91	0.5%
4	27,766	27,682	85	0.3%
5	33,036	33,001	34	0.1%
6	32,740	32,740	0	0.0%
7	33,831	33,831	0	0.0%
8	33,831	33,831	0	0.0%
9	32,505	32,475	30	0.1%
10	27,283	27,183	101	0.4%
11	20,939	20,856	83	0.4%
12	12,306	12,200	105	0.9%
Annual	**295,011**	**294,267**	**744**	**0.3%**

Table A26. Effect of film on HVAC energy performance: simulated electricity consumption in Houston TX.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	103,143	100,152	2,991	2.9%
2	125,005	122,145	2,861	2.3%
3	169,310	165,649	3,661	2.2%
4	213,693	209,126	4,567	2.1%
5	260,346	254,731	5,615	2.2%
6	295,864	287,333	8,531	2.9%
7	320,252	310,522	9,730	3.0%
8	330,927	320,465	10,462	3.2%
9	278,918	271,387	7,531	2.7%
10	211,245	206,884	4,361	2.1%
11	176,524	172,528	3,996	2.3%
12	127,385	124,149	3,236	2.5%
Annual	**2,612,613**	**2,545,072**	**67,542**	**2.6%**

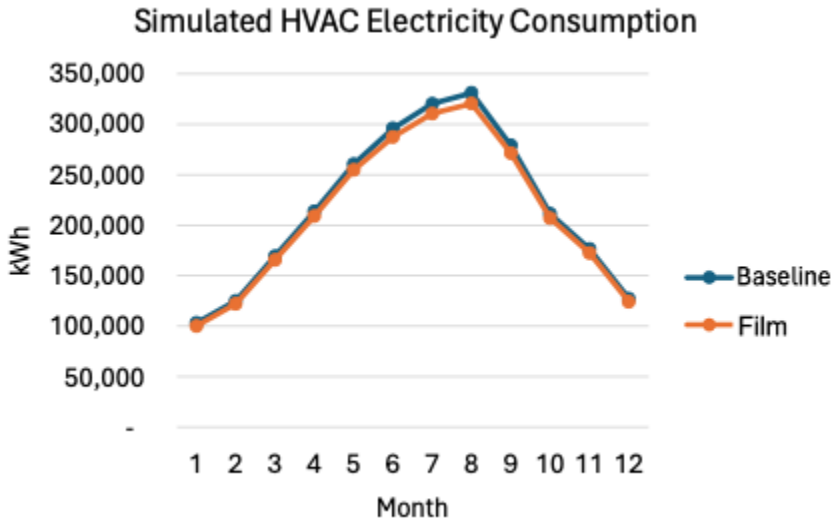


Figure A20. Effect of film on HVAC energy performance: simulated electricity consumption.

Table A27. Effect of film on HVAC energy performance: simulated heating natural gas consumption in Houston TX.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	249,932	267,430	-17,498	-7.0%
2	214,124	226,073	-11,949	-5.6%
3	107,319	115,777	-8,458	-7.9%
4	30,822	34,558	-3,737	-12.1%
5	1,879	2,095	-216	-11.5%
6	0	0	0	0.0%
7	0	0	0	0.0%
8	0	0	0	0.0%
9	0	0	0	0.0%
10	36,822	41,069	-4,246	-11.5%
11	90,852	100,193	-9,341	-10.3%
12	191,718	207,570	-15,852	-8.3%
Annual	**923,469**	**994,765**	**-71,296**	**-7.7%**

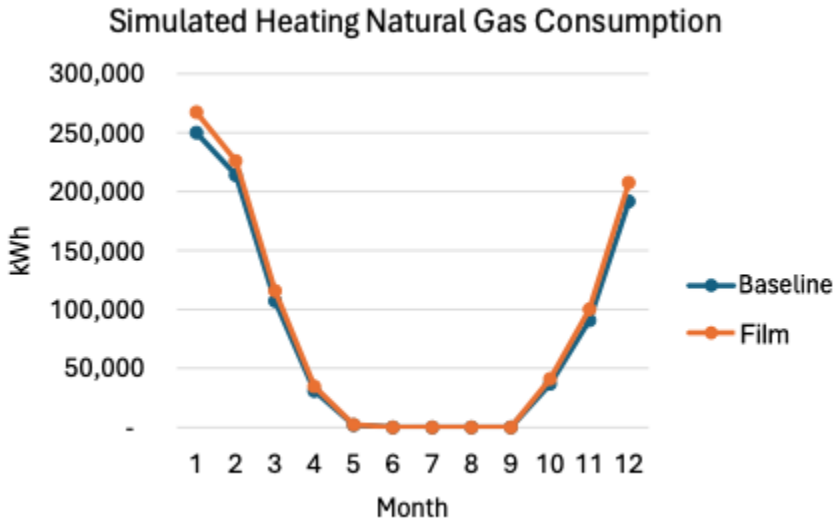


Figure A21. Effect of film on HVAC energy performance: simulated heating natural gas consumption.

Table A28. Effect of film on HVAC peak electricity demand in Houston TX.

Month	Baseline HVAC Peak [kW]	Film HVAC Peak [kW]	Peak Time	Reduction [%]
1	315	312	01/27 16:00	1.0%
2	337	330	02/21 16:00	1.9%
3	398	385	03/24 11:00	3.3%
4	397	384	04/10 11:00	3.2%
5	465	445	05/30 17:00	4.1%
6	454	439	06/30 16:00	3.2%
7	507	489	07/31 12:00	3.5%
8	531	514	08/04 17:00	3.2%
9	455	440	09/22 17:00	3.3%

Month	Baseline HVAC Peak [kW]	Film HVAC Peak [kW]	Peak Time	Reduction [%]
10	455	442	10/02 11:00	3.0%
11	390	377	11/22 16:00	3.3%
12	392	379	12/08 10:00	3.3%

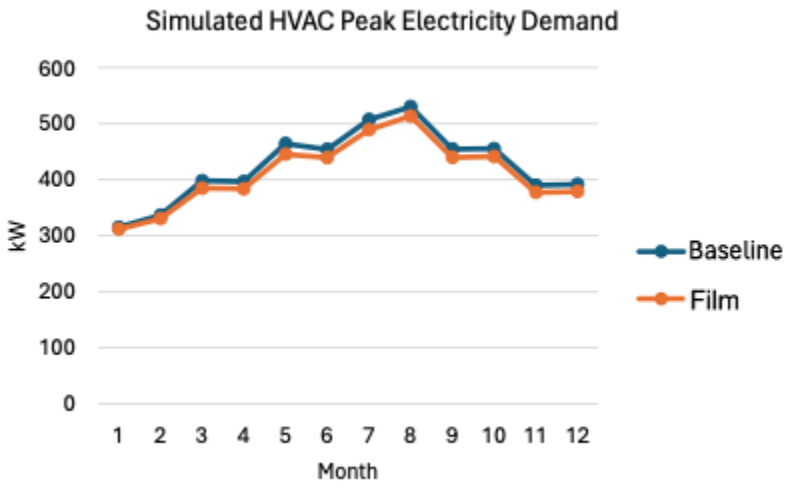


Figure A22. Effect of film on HVAC peak electricity demand.

Table A29. Effect of film on HVAC electricity performance: simulated cooling electricity [kWh] in Phoenix AZ.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	33,331	32,617	714	2.1%
2	49,189	48,426	763	1.6%
3	69,936	69,004	932	1.3%
4	103,360	102,148	1,211	1.2%
5	126,635	124,921	1,715	1.4%
6	147,701	144,530	3,172	2.1%
7	182,874	177,842	5,033	2.8%
8	172,162	167,587	4,575	2.7%
9	136,019	133,366	2,653	2.0%
10	120,560	118,803	1,757	1.5%
11	77,049	76,141	909	1.2%
12	23,850	23,293	557	2.3%
Annual	**1,242,668**	**1,218,677**	**23,990**	**1.9%**

Table A30. Effect of film on HVAC electricity performance: simulated fan electricity [kWh] in Phoenix AZ.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	81,471	78,747	2,723	3.3%
2	73,610	71,144	2,466	3.4%
3	81,495	78,765	2,730	3.3%
4	79,054	76,377	2,677	3.4%
5	82,375	79,475	2,899	3.5%
6	84,209	81,021	3,188	3.8%
7	88,217	85,007	3,211	3.6%
8	86,589	83,404	3,185	3.7%
9	81,105	78,093	3,011	3.7%
10	82,330	79,373	2,956	3.6%
11	78,845	76,208	2,637	3.3%
12	81,471	78,747	2,723	3.3%
Annual	**980,769**	**946,361**	**34,409**	**3.5%**

Table A31. Effect of film on HVAC electricity performance: simulated pump electricity [kWh] in Phoenix AZ.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	2,151	2,142	9	0.4%
2	2,486	2,469	17	0.7%
3	3,196	3,188	8	0.3%
4	3,800	3,788	13	0.3%
5	4,257	4,235	22	0.5%
6	4,429	4,397	32	0.7%
7	4,890	4,846	44	0.9%
8	4,782	4,740	42	0.9%
9	4,364	4,330	35	0.8%
10	4,232	4,204	28	0.7%
11	3,423	3,418	6	0.2%
12	1,702	1,696	6	0.4%
Annual	**43,712**	**43,452**	**260**	**0.6%**

Table A32. Effect of film on HVAC electricity performance: simulated cooling tower electricity [kWh] in Phoenix AZ.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	9,488	9,350	138	1.5%
2	14,548	14,418	130	0.9%
3	20,427	20,270	157	0.8%
4	27,478	27,403	74	0.3%
5	32,034	31,997	37	0.1%
6	31,446	31,446	0	0.0%
7	32,494	32,494	0	0.0%
8	32,494	32,494	0	0.0%
9	31,446	31,446	0	0.0%
10	30,530	30,503	26	0.1%
11	21,828	21,677	150	0.7%
12	6,960	6,837	123	1.8%
Annual	**291,174**	**290,336**	**838**	**0.3%**

Table A33. Effect of film on HVAC energy performance: simulated electricity consumption in Phoenix AZ.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	126,442	122,858	3,584	2.8%
2	139,834	136,458	3,376	2.4%
3	175,055	171,228	3,827	2.2%
4	213,692	209,716	3,976	1.9%
5	245,301	240,628	4,673	1.9%
6	267,785	261,393	6,392	2.4%
7	308,476	300,189	8,287	2.7%
8	296,027	288,225	7,802	2.6%
9	252,934	247,235	5,699	2.3%
10	237,651	232,884	4,768	2.0%
11	181,146	177,444	3,702	2.0%
12	113,986	110,576	3,410	3.0%
Annual	**2,558,329**	**2,498,833**	**59,496**	**2.3%**

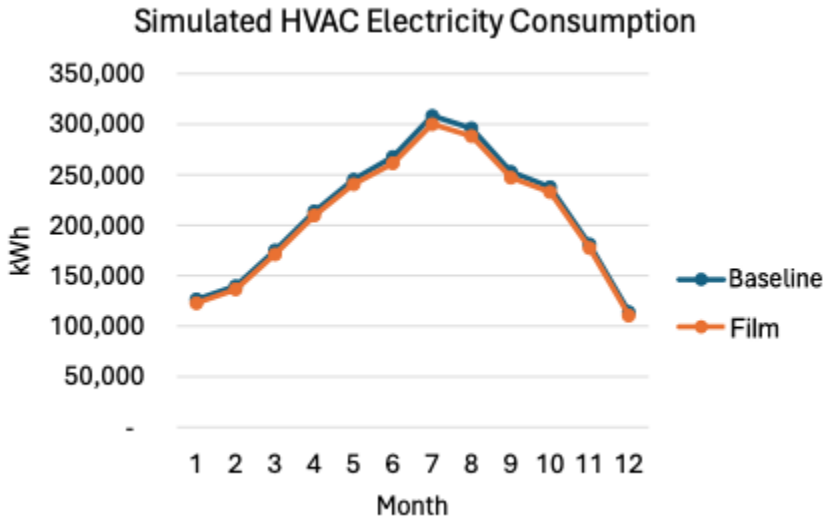


Figure A23. Effect of film on HVAC energy performance: simulated electricity consumption.

Table A34. Effect of film on HVAC energy performance: simulated heating natural gas consumption in Phoenix AZ.

Month	Baseline	Film	Saving [kWh]	Saving [%]
1	126,771	148,921	-22,150	-17.5%
2	112,847	126,652	-13,805	-12.2%
3	61,826	68,647	-6,822	-11.0%
4	25,185	28,201	-3,016	-12.0%
5	1,168	1,442	-274	-23.5%
6	0	0	0	0.0%
7	0	0	0	0.0%
8	0	0	0	0.0%
9	0	0	0	0.0%
10	6,019	7,109	-1,089	-18.1%

11	43,891	54,761	-10,870	-24.8%
12	159,357	186,622	-27,265	-17.1%
Annual	**537,064**	**622,355**	**-85,291**	**-15.9%**

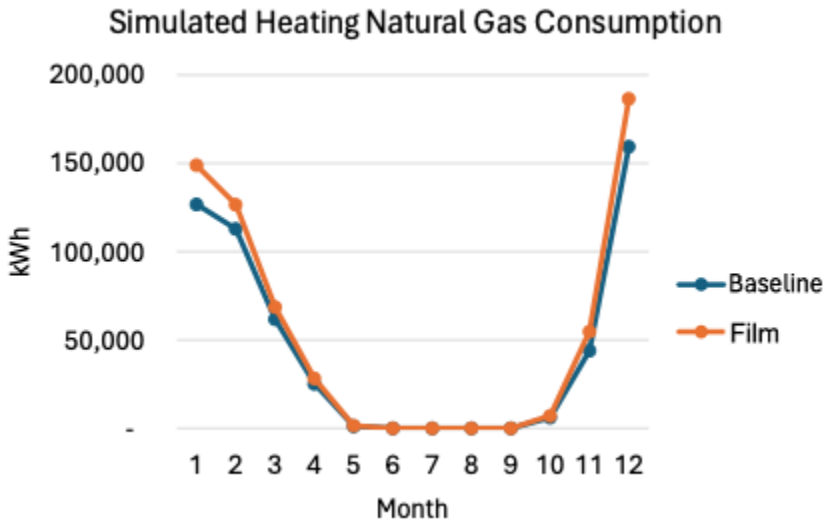


Figure A24. Effect of film on HVAC energy performance: simulated heating natural gas consumption.

Table A35. Effect of film on HVAC peak electricity demand in Phoenix AZ.

Month	Baseline HVAC Peak [kW]	Film HVAC Peak [kW]	Peak Time	Reduction [%]
1	323	319	01/10 17:00	1.2%
2	348	339	02/27 17:00	2.5%
3	334	326	03/14 16:00	2.2%
4	377	363	04/26 17:00	3.9%
5	410	394	05/18 17:00	3.8%

6	497	479	06/27 16:00	3.6%
7	552	533	07/25 16:00	3.5%
8	562	544	08/10 16:00	3.2%
9	463	446	09/01 17:00	3.7%
10	421	402	10/13 16:00	4.5%
11	323	319	11/21 16:00	1.2%
12	322	319	12/20 16:00	1.1%

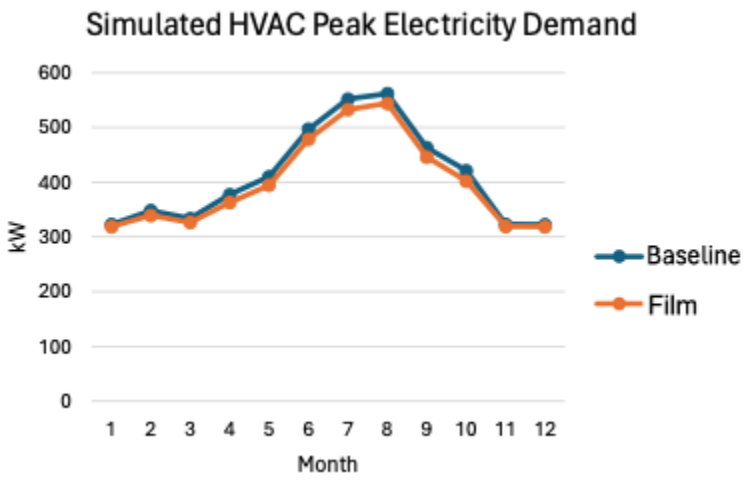


Figure A25. Effect of film on HVAC peak electricity demand.

Occupant Survey Form

1. Please assign a rating from 1 to 9 (or N/A = not applicable) to the following conditions in your office/cubicle area.

Temperature in warm/hot weather	Too cold				Just right				Too hot	
a) Before: original windows	1	2	3	4	5	6	7	8	9	N/A
b) After: with window film	1	2	3	4	5	6	7	8	9	N/A

Do you have any comments on the temperature in warm/hot weather in our office/cubicle area before and after the installation of the window film (e.g., is there a certain time of day when you noticed more of a difference)? Please enter them here.

Light level	Too dark				Just right				Too bright
a) Before: original windows	1	2	3	4	5	6	7	8	9
b) After: with window film	1	2	3	4	5	6	7	8	9

Do you have any comments on the light level in our office/cubicle area before and after the installation of the window film (e.g., is there a certain time of day when you noticed more of a difference)? Please enter them here.

Glare from windows	Not perceptible		Perceptible		Acceptable		Uncomfortable		Intolerable	
a) Before: original windows	1	2	3	4	5	6	7	8	9	N/A
b) After: with window film	1	2	3	4	5	6	7	8	9	N/A

Do you have any comments on the glare from the windows in our office/cubicle area before and after the installation of the window film (e.g., is there a certain time of day when you noticed more of a difference, or did you find less need for shades on the windows)? Please enter them here.

2. Overall, how satisfied are you with the window film versus the original windows? (E.g., 9 means that you were much more satisfied with the window film than with the original configuration.)

	Much less satisfied		Less satisfied		No difference		More satisfied		Much more satisfied
Satisfaction: window film vs. original	1	2	3	4	5	6	7	8	9

3. Overall, would you prefer the windows in your area to have film or left in their original condition?
   a) Window film
   b) Windows in the original condition

4. On which side of the building would you say your office/cubicle area is located?
   a) North (towards W 6th Ave)
   b) South (towards Building 67's main parking lot and public entrance)
   c) East (towards Downtown Denver)
   d) West (towards the Front Range)

5. Approximately, how far away is your office/cubicle area from the nearest window?
   a) 15 feet or less
   b) More than 15 feet

6. Did you notice any change in cell reception after the installation of the window film?

7. Any additional comments you may have on the windows in/near your office/cubicle area would be very helpful. Please enter them here.

8. I consent to be contacted by the project team regarding my responses.
   a. Yes
   b. No