End-Use Savings Shapes Measure Documentation: Window Film

Janghyun Kim, Chris CaraDonna, and Andrew Parker

National Renewable Energy Laboratory

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Technical Report
NREL/TP-5500-86554
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List of Acronyms

AEDG	Advanced Energy Design Guide
HVAC	heating, ventilating, and air conditioning
IGU	insulated glass unit
LBNL	Lawrence Berkeley National Laboratory
low-E	low emissivity
SCF	solar control film
SHGC	solar heat gain coefficient
VLT	visual light transmittance

Executive Summary

Building on the successfully completed effort to calibrate and validate the U.S. Department of Energy's ResStock™ and ComStock™ models over the past three years, the objective of this work is to produce national data sets that empower analysts working for federal, state, utility, city, and manufacturer stakeholders to answer a broad range of analysis questions.

The goal of this work is to develop energy efficiency, electrification, and demand flexibility end-use load shapes (electricity, gas, propane, or fuel oil) that cover a majority of the high-impact, market-ready (or nearly market-ready) measures. "Measures" refers to energy efficiency variables that can be applied to buildings during modeling.

An *end-use savings shape* is the difference in energy consumption between a baseline building and a building with an energy efficiency, electrification, or demand flexibility measure applied. It results in a timeseries profile that is broken down by end use and fuel (electricity or on-site gas, propane, or fuel oil use) at each timestep.

ComStock is a highly granular, bottom-up model that uses multiple data sources, statistical sampling methods, and advanced building energy simulations to estimate the annual subhourly energy consumption of the commercial building stock across the United States. The baseline model intends to represent the U.S. commercial building stock as it existed in 2018. The methodology and results of the baseline model are discussed in the final technical report of the End-Use Load Profiles project.

This documentation focuses on a single end-use savings shape measure—window film. The window film studied in this analysis, called solar control film, is a passive retrofit solution for windows that does not involve window replacement. This type of film consists of transparent, tinted, or metalized laminated polyester layers and can be applied to an existing window surface (either on the exterior or interior side of the window). The properties of the window film are designed to alter the thermal and optical performances of the overall glazing system to meet the various needs of the building occupants (e.g., heat, glare).

While the practical goal of purchasing and installing a window film varies widely in the real market, this study focuses only on the goal of energy savings and highlights the corresponding emissions. Other important aspects that building occupants typically consider are visual comfort, privacy, aesthetics, ultraviolet protection, etc. In practice, customers therefore often choose a window film product not only to save energy (or cost) but also to mitigate problems with glare, excessive light, daytime privacy, or inconsistent appearance of the building.

The window film products modeled in this analysis significantly reduce the solar heat gain coefficient of the entire glazing system, resulting in better energy savings for buildings in hot climate regions. However, a significant reduction in the solar heat gain coefficient that reduces unfavorable heat gain in summer can also lower favorable heat gain in winter. By applying window films on a stock of buildings covering various load and weather conditions, this analysis highlights when (e.g., time of day) and where (e.g., geographical location) window films can save energy.

Acknowledgments

The authors would like to acknowledge the valuable guidance and input provided by Shanti Pless and Marcus Bianchi at NREL and Jen Daly at 3M.

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1 Window Film

1.1 Accessing Results

This documentation covers window film upgrade methodology and briefly discusses key results. Results can be accessed on the ComStock data lake "end-use-load-profiles-for-us-building-stock" or via the Data Viewer at comstock.nrel.gov.

1.2 Measure Summary

Measure Title	Window Film
Measure Definition	This measure applies new performance of the overall glazing system reflecting a scenario when an applicable window film is attached to the original ("baseline") window.
Applicability	Certain window film (based on real products in the market) is determined by (1) baseline window type and (2) climate zone.
Not Applicable	Triple pane windows are considered not applicable for buildings in any climate zone. Double pane windows in buildings in very cold regions are considered not applicable.
Release	EUSS 2023 Release 1

2 Technology Summary

Window films, especially solar control films (SCFs), are a passive retrofit solution for windows that do not require complete window replacement. The following is a summary of SCF technology from a 2022 literature review published in *Applied Sciences* [1].

- SCF—composed of transparent, tinted, or metalized laminated polyester layers—is designed to shift thermal and solar optical properties of the overall glazing system by differently (compared to window without film) reflecting or absorbing part of the incident solar radiation. SCF promotes the improvement of the thermal and luminous performance of building glazing while reducing potential glare and the transmittance of ultraviolet radiation. The manufacturers of window films offer a wide range of performances depending on different use cases (e.g., energy savings, mitigating glare, controlling occupant's view, protecting privacy).

- Figure 1 shows different film positions (e.g., Class A to D) with respect to typical insulated glass units (IGUs). While indoor films are more common than outdoor films in the current market, some of the latest outdoor films provide better energy performance when applied on relatively high-performing windows (e.g., double pane low-E), and some of those products are currently being studied in real applications [2].

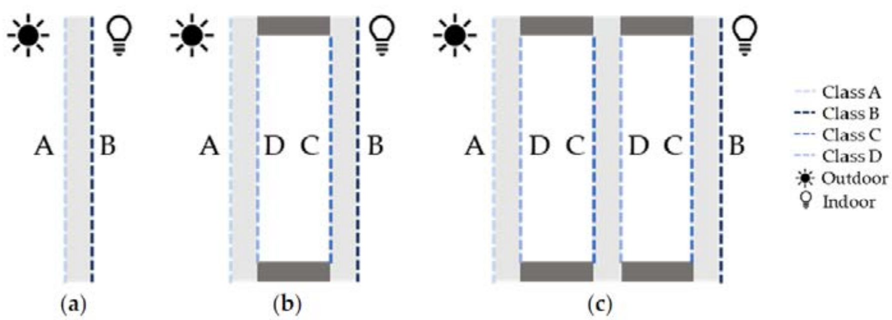

Figure 1. Different installation positions of window films for (a) single pane, (b) double pane, and (c) triple pane windows

Figure from [1]

- Types of SCFs can vary, driven by different use cases:
  - Reflective type
    - Has reflective properties on both sides
    - Mitigates high heat, glare, and ultraviolet control

        - Has a silvery/mirrored look to the glazing when viewed with indoor lighting or outdoor daylight.

- Dual-reflective type
    - Has reflective outside-facing layer with a subtler inside-facing layer
    - Mitigates significant solar control during the day
    - Maintains clear outside view at night.

- Neutral type
    - Controls solar gains through the glass
    - Maintains original appearance of the glazing system.

- Low emissivity type
    - Reduces the thermal transmittance coefficient (U-value) of the glazing system
    - Increases thermal insulation and heat rejection properties
    - Suitable for temperate regions.

- Spectrally selective type
    - Offers an excellent heat rejection with a virtually invisible appearance
    - Blocks specific regions of the solar spectrum associated with solar heat gains
    - Does not penalize transmittance of daylight through the glazing.

- Ceramic type
    - Offers solar control without a metal layer
    - Maintains low visible reflectivity and high resistance to corrosion
    - Suitable for coastal areas.

- Safety and protection type
    - Controls excessive solar heat gains
    - Increases the resistance of the glass pane to intentional or accidental impacts
    - Reduces amount and dimension of potential glass fragments
    - Offers higher resistance to the glass to support shock waves from explosions and/or ballistic attacks.

- Manufacturers provide standardized data for SCFs through the National Fenestration Rating Council's guidelines and the International Glazing Database, which can be used for additional analysis such as building energy modeling. Figure 2 shows the number of SCF models in the International Glazing Database (v72.0). Models included in the International Glazing Database can be imported to Lawrence Berkeley National Laboratory's (LBNL) WINDOW[1] software for either calculating (1) simplified (center-of-glass) properties (e.g., solar heat gain coefficient, U-value, visual light transmittance) or (2) detailed properties (e.g., varying solar heat gain coefficient by solar angular dependence) that can be also used in EnergyPlus™ for building energy simulations.

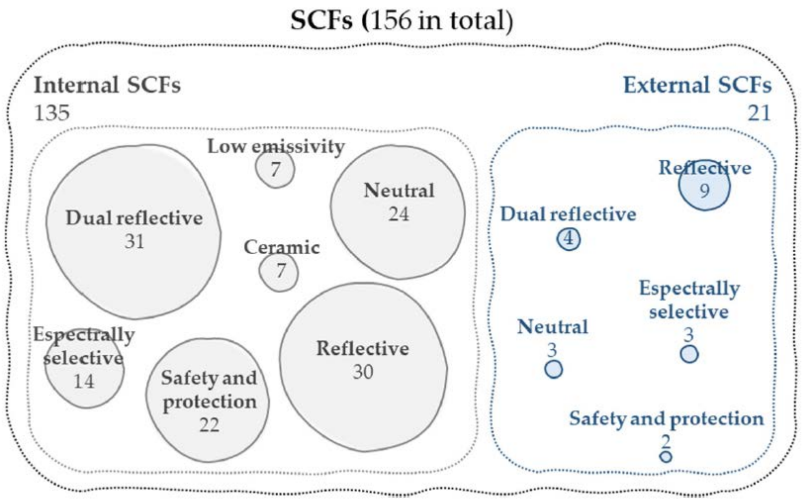

Figure 2. Number and type of SCFs in the International Glazing Database

Figure from [1]

SCF products are available from various manufacturers covering various ranges of thermal (e.g., U-value, SHGC) and optical (e.g., transmittance and reflectance of light) performances as shown in Figure 3. Plots shown in Figure 3 indicate performance (i.e., U-value, SHGC, visual light transmittance, and visual light reflectance) of windows when certain window film (i.e., All Season to Prestige Exterior Series) is applied on four different baseline windows (i.e., clear single pane, tinted single pane, clear double pane, and tinted double pane). Multiple markers in each row represent different models (e.g., Low E 20, Low E 35) in a series (e.g., All Season) with varying tint levels. These window performance calculations were performed by the manufacturer using LBNL's WINDOW software. As shown in Figure 3, customers can select from a wide range of products based on various needs between thermal goals (e.g., summer heat gain is too high) and visual goals (e.g., glare inside of the building is too much).

[1] For more information, see https://windows.lbl.gov/software/window.

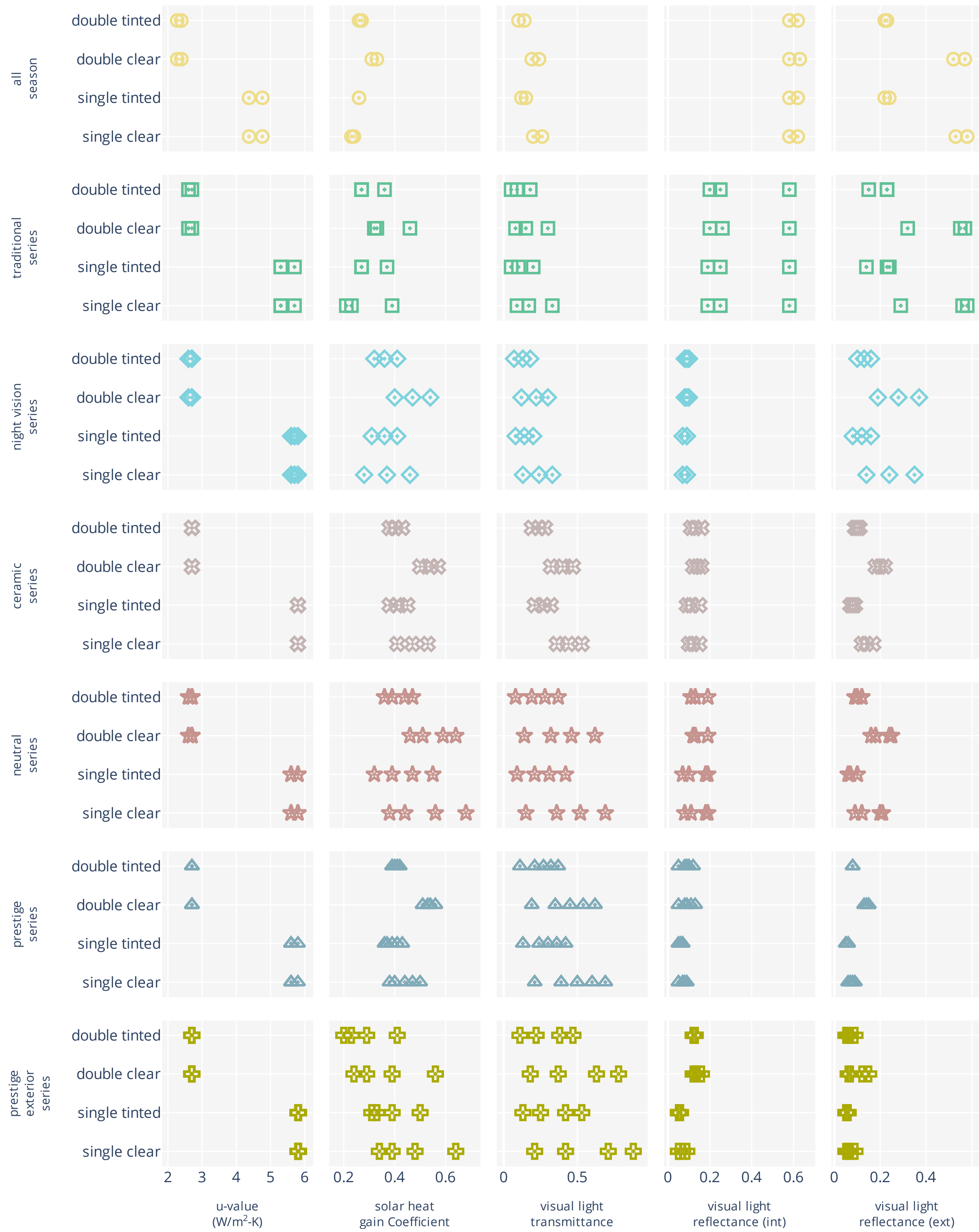

Figure 3. Performance characteristics and variations of SCFs from 3M

3 ComStock Baseline Approach

The current baseline building stock in ComStock has 12 different window configurations. Figure 4 shows the breakdown of windows by total floor area. In total, single pane windows represent about 53% of the floor area, double pane 47%, and triple pane <1%. The window film measure is applicable to all buildings that currently have single or double pane windows, which is nearly 100% of the stock. The very small fraction of buildings that already have triple pane windows do not receive this upgrade in our modeling.

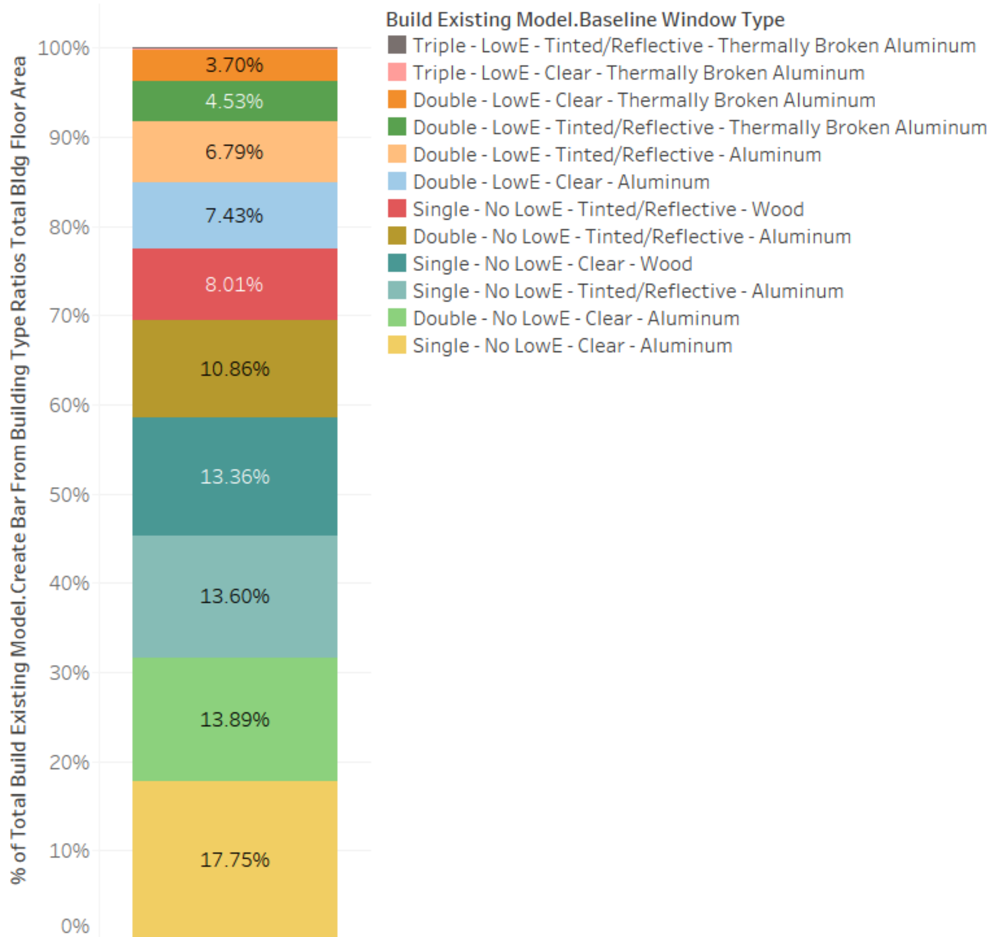

Figure 4. Floor area portion of different baseline window types across the entire building stock in ComStock

4 Modeling Approach

4.1 Technology Specifications

It is possible to achieve a wide range of thermal and optical performances with an IGU that is composed of glass, spacer, gas, frame, and with and without window film. Because of the differences in climates across the United States, it is not desirable to drive the performance of the IGU in one direction (i.e., tradeoff is required); warmer climates with high cooling requirements may want lower SHGC to avoid overheating, while higher SHGC may be preferable to allow beneficial solar gain in colder climates. As a starting point for the target IGU performance, the performance properties from ASHRAE's *Achieving Zero Energy: Advanced Energy Design Guide (AEDG) for Small to Medium Office Buildings* [3] are documented, as shown in Table 1.

Table 1. Overall Assembly Performance Characteristics by Climate Zone

Climate zone	0	1	2	3	4	5	6	7	8
U-factor (Btu/hr-ft^2-°F)	0.48	0.48	0.43	0.40	0.34	0.34	0.32	0.28	0.25
SHGC (-)	0.21	0.22	0.24	0.24	0.34	0.36	0.36	0.38	0.38
VLT/SHGC (-)	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10

To understand the expected performance of the total assembly, combinations of existing windows and window films are modeled using LBNL's WINDOW (v7.8) and Optics (v6) software, shown in Figure 5. Table 2 includes (1) performance (e.g., U-factor, SHGC, and visual light transmittance [VLT]) improvements between ComStock baseline windows and windows with window films; and (2) performance comparison against AEDG targets, with respect to different climate zones. Several window film products were selected from a larger pool (shown in Figure 3) based on the emphasis on thermal performance improvements rather than visual performance improvements, as this analysis is focused on the energy savings potential.

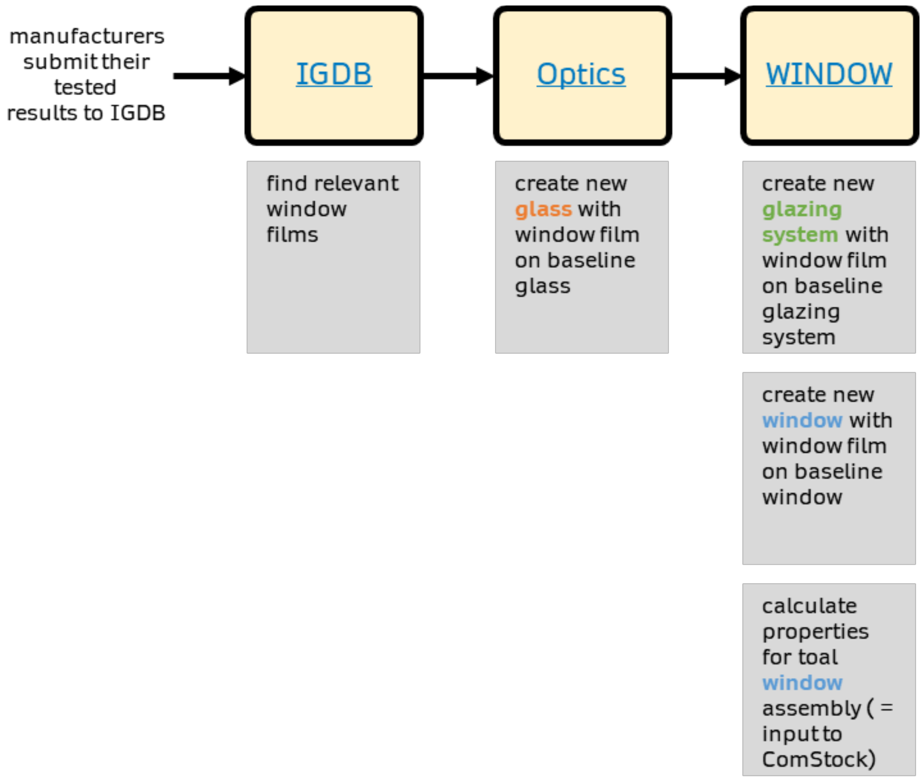

Figure 5. Workflow of creating new glass, glazing systems, and windows with window films

Table 2. Performance Range Baseline Windows with Window Films

Baseline Window Configuration				Window Film Retrofit Options		Retrofit Compared to Baseline		Baseline Compared to AEDG ZE						Retrofit Compared to AEDG ZE					
								U-factor within 10%?			SHGC within 10%?			U-factor within 10%?			SHGC within 10%?		
Pane	Low-E	Glazing	Frame	Film Position	Film Product	U-factor	SHGC	CZ 1, 2, 3	CZ 4, 5, 6	CZ 7, 8	CZ 1, 2, 3	CZ 4, 5, 6	CZ 7, 8	CZ 1, 2, 3	CZ 4, 5, 6	CZ 7, 8	CZ 1, 2, 3	CZ 4, 5, 6	CZ 7, 8
Single	No	Clear	Aluminum	Interior	Affinity 15	1%	68%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Single	No	Clear	Aluminum	Interior	Affinity 30	3%	49%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Single	No	Clear	Aluminum	Interior	Low e 20	18%	67%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Single	No	Clear	Aluminum	Interior	Low e 35	14%	68%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Single	No	Clear	Aluminum	Exterior	Prestige exterior 20	0%	55%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Single	No	Clear	Aluminum	Exterior	Prestige exterior 70	0%	39%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Single	No	Tinted/Reflective	Aluminum	Interior	Affinity 15	1%	51%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Single	No	Tinted/Reflective	Aluminum	Interior	Affinity 30	3%	39%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Single	No	Tinted/Reflective	Aluminum	Interior	Low e 20	18%	55%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Single	No	Tinted/Reflective	Aluminum	Interior	Low e 35	14%	54%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Single	No	Tinted/Reflective	Aluminum	Exterior	Prestige exterior 20	0%	48%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Single	No	Tinted/Reflective	Aluminum	Exterior	Prestige exterior 70	0%	35%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Single	No	Clear	Wood	Interior	Affinity 15	1%	71%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE

Baseline Window Configuration				Window Film Retrofit Options		Retrofit Compared to Baseline		Baseline Compared to AEDG ZE						Retrofit Compared to AEDG ZE					
								U-factor within 10%?			SHGC within 10%?			U-factor within 10%?			SHGC within 10%?		
Pane	Low-E	Glazing	Frame	Film Position	Film Product	U-factor	SHGC	CZ 1, 2, 3	CZ 4, 5, 6	CZ 7, 8	CZ 1, 2, 3	CZ 4, 5, 6	CZ 7, 8	CZ 1, 2, 3	CZ 4, 5, 6	CZ 7, 8	CZ 1, 2, 3	CZ 4, 5, 6	CZ 7, 8
Single	No	Clear	Wood	Interior	Affinity 30	4%	51%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Single	No	Clear	Wood	Interior	Low e 20	22%	70%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Single	No	Clear	Wood	Interior	Low e 35	17%	71%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Single	No	Clear	Wood	Exterior	Prestige exterior 20	0%	58%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Single	No	Clear	Wood	Exterior	Prestige exterior 70	0%	41%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE
Single	No	Tinted/Reflective	Wood	Interior	Affinity 15	1%	54%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Single	No	Tinted/Reflective	Wood	Interior	Affinity 30	4%	41%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Single	No	Tinted/Reflective	Wood	Interior	Low e 20	22%	58%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
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Single	No	Tinted/Reflective	Wood	Exterior	Prestige exterior 20	0%	51%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
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Double	No	Clear	Aluminum	Interior	Low e 20	8%	50%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Double	No	Clear	Aluminum	Interior	Low e 35	6%	53%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Double	No	Clear	Aluminum	Exterior	Prestige exterior 20	0%	62%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	No	Clear	Aluminum	Exterior	Prestige exterior 70	0%	42%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Double	No	Tinted/Reflective	Aluminum	Interior	Affinity 15	0%	44%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Double	No	Tinted/Reflective	Aluminum	Interior	Affinity 30	1%	29%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Double	No	Tinted/Reflective	Aluminum	Interior	Low e 20	8%	46%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Double	No	Tinted/Reflective	Aluminum	Interior	Low e 35	6%	49%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	No	Tinted/Reflective	Aluminum	Exterior	Prestige exterior 20	0%	56%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	No	Tinted/Reflective	Aluminum	Exterior	Prestige exterior 70	0%	39%	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Double	Yes	Clear	Aluminum	Interior	Affinity 15	0%	39%	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Clear	Aluminum	Interior	Affinity 30	1%	20%	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Double	Yes	Clear	Aluminum	Interior	Low e 20	4%	37%	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Clear	Aluminum	Interior	Low e 35	3%	41%	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Clear	Aluminum	Exterior	Prestige exterior 20	0%	60%	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Clear	Aluminum	Exterior	Prestige exterior 70	0%	25%	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Double	Yes	Clear	Aluminum with thermal break	Interior	Affinity 15	0%	39%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Clear	Aluminum with thermal break	Interior	Affinity 30	1%	20%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Double	Yes	Clear	Aluminum with thermal break	Interior	Low e 20	5%	38%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Clear	Aluminum with thermal break	Interior	Low e 35	4%	42%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Clear	Aluminum with thermal break	Exterior	Prestige exterior 20	0%	61%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Clear	Aluminum with thermal break	Exterior	Prestige exterior 70	0%	25%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE

Baseline Window Configuration				Window Film Retrofit Options		Retrofit Compared to Baseline		Baseline Compared to AEDG ZE						Retrofit Compared to AEDG ZE					
								U-factor within 10%?			SHGC within 10%?			U-factor within 10%?			SHGC within 10%?		
Pane	Low-E	Glazing	Frame	Film Position	Film Product	U-factor	SHGC	CZ 1, 2, 3	CZ 4, 5, 6	CZ 7, 8	CZ 1, 2, 3	CZ 4, 5, 6	CZ 7, 8	CZ 1, 2, 3	CZ 4, 5, 6	CZ 7, 8	CZ 1, 2, 3	CZ 4, 5, 6	CZ 7, 8
Double	Yes	Tinted/Reflective	Aluminum	Interior	Affinity 15	0%	32%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Tinted/Reflective	Aluminum	Interior	Affinity 30	1%	17%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Tinted/Reflective	Aluminum	Interior	Low e 20	4%	32%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Tinted/Reflective	Aluminum	Interior	Low e 35	3%	35%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Tinted/Reflective	Aluminum	Exterior	Prestige exterior 20	0%	53%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Tinted/Reflective	Aluminum	Exterior	Prestige exterior 70	0%	22%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Tinted/Reflective	Aluminum with thermal break	Interior	Affinity 15	0%	34%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Tinted/Reflective	Aluminum with thermal break	Interior	Affinity 30	1%	17%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Tinted/Reflective	Aluminum with thermal break	Interior	Low e 20	5%	33%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Tinted/Reflective	Aluminum with thermal break	Interior	Low e 35	3%	36%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Tinted/Reflective	Aluminum with thermal break	Exterior	Prestige exterior 20	0%	55%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Double	Yes	Tinted/Reflective	Aluminum with thermal break	Exterior	Prestige exterior 70	0%	23%	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
Triple	Yes	Clear	Aluminum with thermal break	n/a	n/a	n/a	n/a	TRUE	TRUE	FALSE	FALSE	TRUE	TRUE	n/a	n/a	n/a	n/a	n/a	n/a
Triple	Yes	Tinted/Reflective	Aluminum with thermal break	n/a	n/a	n/a	n/a	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	n/a	n/a	n/a	n/a	n/a	n/a

Table 2 shows performance comparisons between all baseline windows considered in ComStock versus window films considered. As shown in the two “retrofit compared to baseline” columns in Table 2, U-factor improvements (i.e., reductions) vary from 0% to 22%, and SHGC improvements (i.e., reductions) vary from 17% to 71% when applying window films on different baseline windows. As expected, (1) relative improvements with window films are more significant on SHGC rather than on U-factor (while low-E coated window films still improve U-factor) and (2) higher SHGC improvements (colored in blue) are mostly seen in lower-performing windows (e.g., clear single pane).

The “baseline compared to AEDG ZE” and “retrofit compared to AEDG ZE” columns in Table 2 indicate whether the performances (i.e., U-factor and SHGC) of either baseline windows or windows with films are close (within 10%) to the target performance suggested by the AEDG shown in Table 1. As shown in Table 2, baseline triple pane windows are mostly (besides one or two extreme cases for U-factor and SHGC) within AEDG performance targets, thus, they do not need window films to meet thermal performance targets. Also, compared to SHGC improvements, attaching window films does not provide enough U-factor improvement to allow the retrofitted windows to meet the AEDG targets.

While many low-E coated double pane baseline windows perform well (in climate zones 4, 5, 6, 7, and 8) in terms of SHGC compared to AEDG targets, attaching a window film on the exterior side (e.g., Prestige Exterior series) of the window can still achieve significant SHGC reduction compared to the baseline windows, meeting the AEDG targets for climate zones 1, 2, and 3. While the material and labor price of exterior films can be higher than interior films and maintenance of exterior films (i.e., exposed to weather) can include additional effort, it may be a good option for hot climates with high cooling loads in terms of energy performance.

4.2 Applicability

Table 3 presents the applicability of the window film measure to ComStock baseline windows. Each row in the table represents (1) one of the baseline windows besides triple pane (i.e., Baseline Window Configuration column), (2) which window film product is paired with the baseline window (i.e., Window Film Retrofit Options column), and (3) how the applicability of the window film is defined between different climate zones (i.e., Applicability with Climate Zone Number Column). While it is expected that the addition of window films might not provide energy savings in the colder climates, all single pane baseline windows are paired with one product for every climate zone as shown in the table to understand both positive and negative impacts. All double pane baseline windows are paired with exterior film that has maximum improvements in SHGC. However, since these exterior films on double pane windows do not offer improvements on U-factor (favorable to winter season) as shown in Table 2, window films are not applied to double pane windows in colder climates (i.e., climate zones 7 and 8).

Table 3. Applicability Criteria of Window Films

Baseline Window Configuration				Baseline Window Performance				Window Film Retrofit Options		Retrofitted Window Performance				Retrofit Compared to Baseline		Applicability with Climate Zone Number
Pane	Low-E	Glazing	Frame	U (SI*)	U (IP**)	SHGC	VLT	Film Position	Film Product	U (SI*)	U (IP**)	SHGC	VLT	U	SHGC	
Single	No	Clear	Aluminum	6.689	1.178	0.744	0.754	Interior	Low E 20	5.502	0.969	0.248	0.170	18%	67%	1,2,3,4,5,6,7,8
Single	No	Tinted/ Reflective	Aluminum	6.688	1.178	0.579	0.455	Interior	Low E 20	5.502	0.969	0.259	0.100	18%	55%	1,2,3,4,5,6,7,8
Single	No	Clear	Wood	5.169	0.910	0.683	0.723	Interior	Low E 20	4.031	0.710	0.208	0.163	22%	70%	1,2,3,4,5,6,7,8
Single	No	Tinted/ Reflective	Wood	5.168	0.910	0.525	0.436	Interior	Low E 20	4.031	0.710	0.219	0.096	22%	58%	1,2,3,4,5,6,7,8
Double	No	Clear	Aluminum	4.238	0.746	0.646	0.671	Exterior	Prestige exterior 20	4.236	0.746	0.246	0.154	0%	62%	1,2,3,4,5,6
Double	No	Tinted/ Reflective	Aluminum	4.255	0.749	0.484	0.411	Exterior	Prestige exterior 20	4.253	0.749	0.214	0.095	0%	56%	1,2,3,4,5,6
Double	Yes	Clear	Aluminum	3.174	0.559	0.386	0.591	Exterior	Prestige exterior 20	3.173	0.559	0.154	0.136	0%	60%	1,2,3,4,5,6
Double	Yes	Clear	Aluminum with thermal break	2.833	0.499	0.378	0.591	Exterior	Prestige exterior 20	2.832	0.499	0.146	0.136	0%	61%	1,2,3,4,5,6
Double	Yes	Tinted/ Reflective	Aluminum	3.160	0.557	0.274	0.359	Exterior	Prestige exterior 20	3.159	0.556	0.129	0.083	0%	53%	1,2,3,4,5,6
Double	Yes	Tinted/ Reflective	Aluminum with thermal break	2.818	0.496	0.266	0.359	Exterior	Prestige exterior 20	2.817	0.496	0.121	0.083	0%	55%	1,2,3,4,5,6

*SI = International system of units
**IP = inch-pound units

4.3 Output Variables of the Measure

Table 4 includes a list of output variables that are being processed in ComStock. These variables are important in terms of understanding the differences between buildings (or IGUs) with and without window films. Additionally, these output variables can also be used for understanding the economics (e.g., return on investment) of the upgrade if cost information (i.e., material, labor, and maintenance cost for window film application) is available.

Table 4. Output Variables Calculated from the Measure Application

Variable Name	Description
Window area	Total area of exterior glazing in Windows (not doors or skylights)
Surface area weighted average U-factor for exterior windows	Window-surface-area-weighted-average U-factor for all exterior windows
Surface area weighted average SHGC for exterior windows	Window-surface-area-weighted-average SHGC for all exterior windows
Surface area weighted average VLT for exterior windows	Window-surface-area-weighted-average VLT for all exterior windows

4.4 Non-Energy Impacts, Limitations, and Concerns

It should be noted that this analysis focuses only on the energy performance of window film application without considering other important aspects: visual comfort, privacy, aesthetics, ultraviolet protection, etc. In practice, customers typically choose a window film product based on their issues around glare and excessive light, too much heat, daytime privacy, inconsistent appearance of the building, and so on. For example, a building might have to comply with historical landmark designations, thus, decisions on window film can even be more complicated in terms of not just considering thermal/visual aspects but also considering how it matches with surrounding buildings. Additionally, museum owners and homeowners may prioritize protecting building interiors (and things placed indoors) from ultraviolet radiation. Thus, more comprehensive research for window films should include these non-energy aspects as well.

In Comstock, window blinds are not included in terms of reflecting the variations of covered and uncovered windows in a building and across the building stock. There can be an office building with high window-to-wall ratio and where a large portion of the glazing is covered with blinds (e.g., to mitigate glare and heat gain near the glazing) for a large amount of time throughout the day. Because the results in this analysis are based on a fully uncovered window for the entire building stock and for the entire simulation period, some level of cooling load overestimation in hotter regions and heating load underestimation in colder regions should be acknowledged.

Finally, there are further analyses that the window film measure can potentially offer beyond the scope of this analysis. Once the cost information can be readily available, a simple payback calculation (considering material and labor cost for initial installation) or a more detailed life cycle assessment (considering material, labor, and maintenance cost) can be performed to understand the economics of window film implementation. While it is unclear what exact format the cost information will be (e.g., cost normalized by window surface area?), output variables such as overall window area and area-weighted average window properties (U-factor, SHGC, and VLT) are calculated (as described in Section 3.3) in ComStock to provide indicators for estimating the cost of the upgrade. Additionally, the window film measure can also be used for quantifying the mitigation or aggravation impact of window films under electrification scenarios. As mentioned previously, window films considered in this analysis mostly improve SHGC of the window that benefits more toward the cooling season. However, if an electrification scenario results in peak shifting from cooling season to heating season (e.g., gas heating converted to electric heating), window films considered in this analysis might even make the peak shifting worse in those scenarios.

5 Results

5.1 Energy Impacts: Single Building Example

The window film shown as "low-E 20" in Table 3 was tested on a small office building model with electric heating, and under both hot and cold weather conditions. Figure 6 and Figure 7 show (1) comparisons between baseline and upgrade simulations, (2) results under hot and cold weather conditions, and (3) results with annual energy consumption metrics and segmented load profiles (i.e., electricity usage on HVAC system). Based on the performance of window films shown in Table 2, it is expected that most of the window film applications that show higher improvements on SHGC (compared to improvements on U-factor) will be favorable for reducing the cooling load in the hotter climate. On the other hand, the same windows that reduce the unfavorable solar heat from the indoor space during the cooling season will then block the favorable solar heat in heating season. This trend of performance difference between hot and cold seasons is depicted well in Figure 6 and Figure 7, respectively.

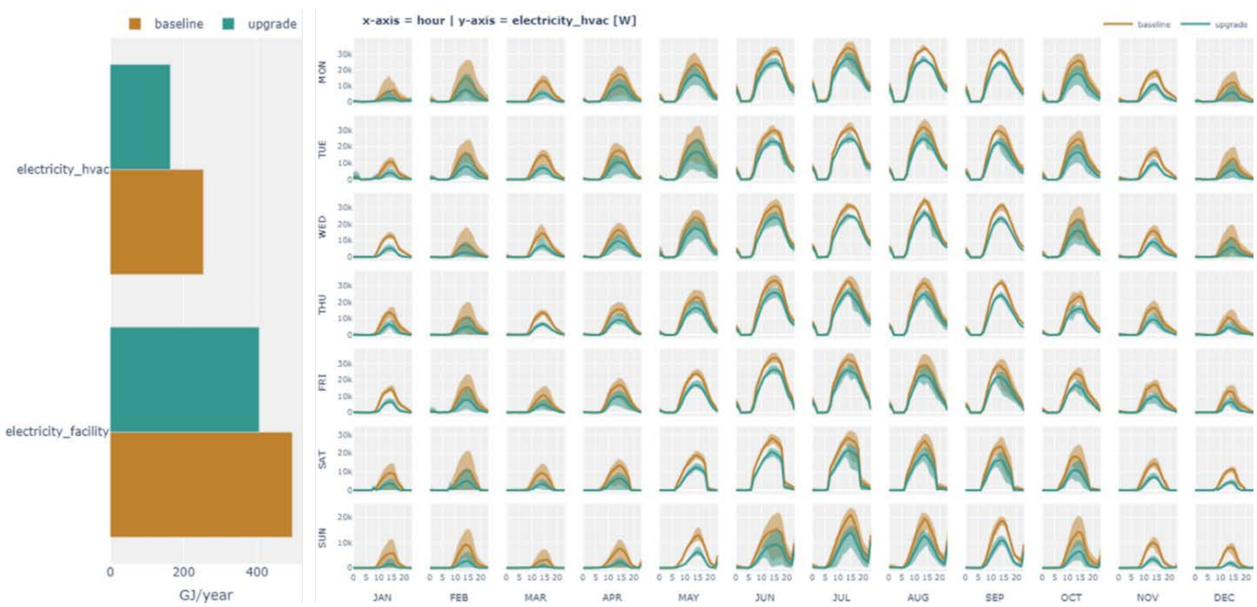

Figure 6. Simulation results with and without window film: hotter region (Tucson, AZ)

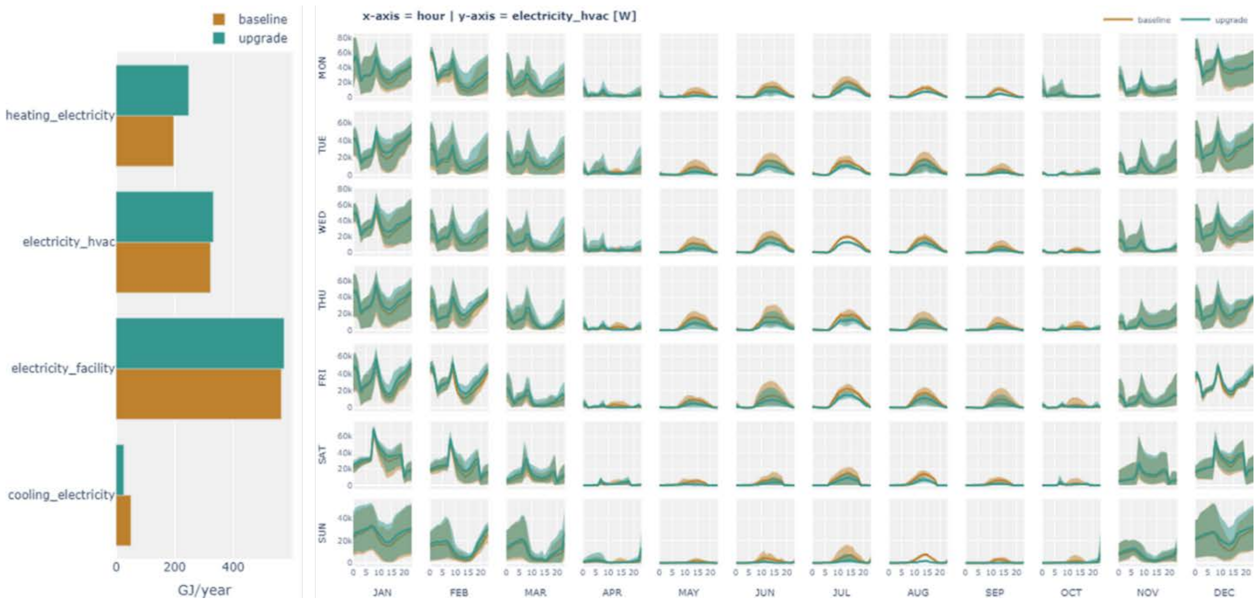

Figure 7. Simulation results with and without window film: colder region (International Falls, MN)

5.2 Energy Impacts: 100 Building Examples

The window film measure was tested on 100 building samples in ComStock. Figure 8 includes average nominal window performances (SHGC, U-factor, and VLT) of 100 building samples between baseline and upgrade scenarios across different climate zones (number next to the bar represents the number of samples/buildings). As expected, windows with window film provide significant reduction in SHGC. Based on the applicability criteria described previously, windows on one sample building (with double pane windows) in climate zone 7 did not receive the window film upgrade, resulting in no change in window performance between the baseline and the upgrade scenario. Also, the relative reduction in U-factor is much less than the reduction in SHGC. The reduction in VLT is highly correlated with the reduction in SHGC, as expected, and while this helps reduce summer cooling load by blocking solar heat gains, reduction in visible light reduces illumination level in the space, resulting in increased interior lighting usage when daylighting is implemented in the building.

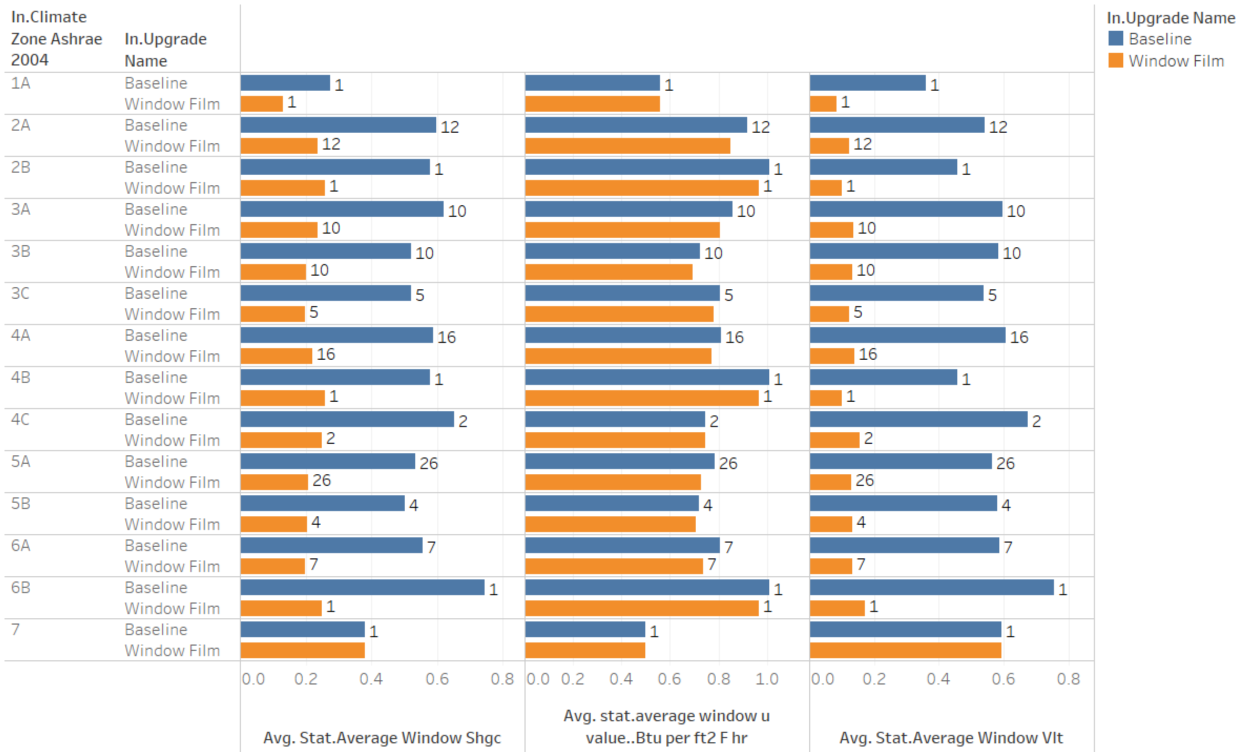

Figure 8. Average window performance of 100 building samples: solar heat gain coefficient, U-factor, and visual light transmittance

Figure 9 shows distributions of energy savings for the 100 building samples across different end uses. The distributions confirm that end uses related to cooling (e.g., electricity cooling, district cooling, and electricity fans) show positive savings while end uses related to heating (e.g., natural gas heating and electricity heating) show negative savings. Some of the models at the edge of the violin plot that show 100% increase in electric heating are mostly attributed to a building in the hotter climate with very small heating load. In these buildings, the addition of window film increased the heating load by a small amount in absolute magnitude but more substantial in terms of relative percentage increase.

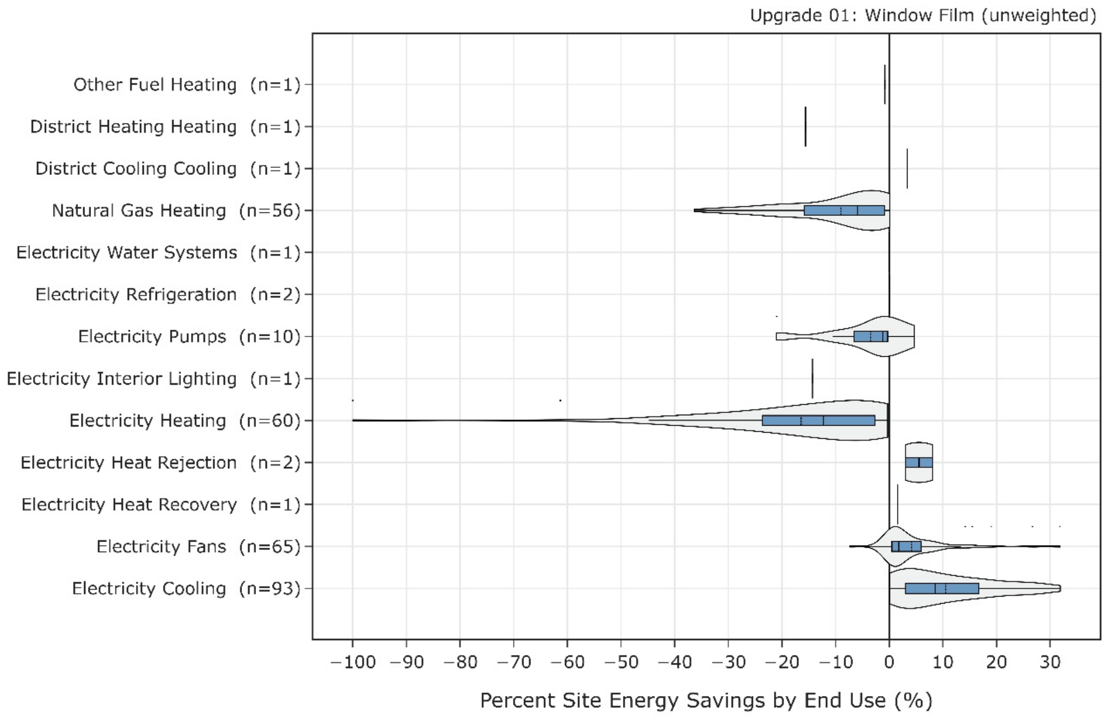

Figure 9. ComStock test results with 100 sample buildings: percent savings by end uses

Figure 10 shows distributions of energy savings for the 100 building samples across different climate zones. The distributions confirm the trend of more savings in the hotter climate zones.

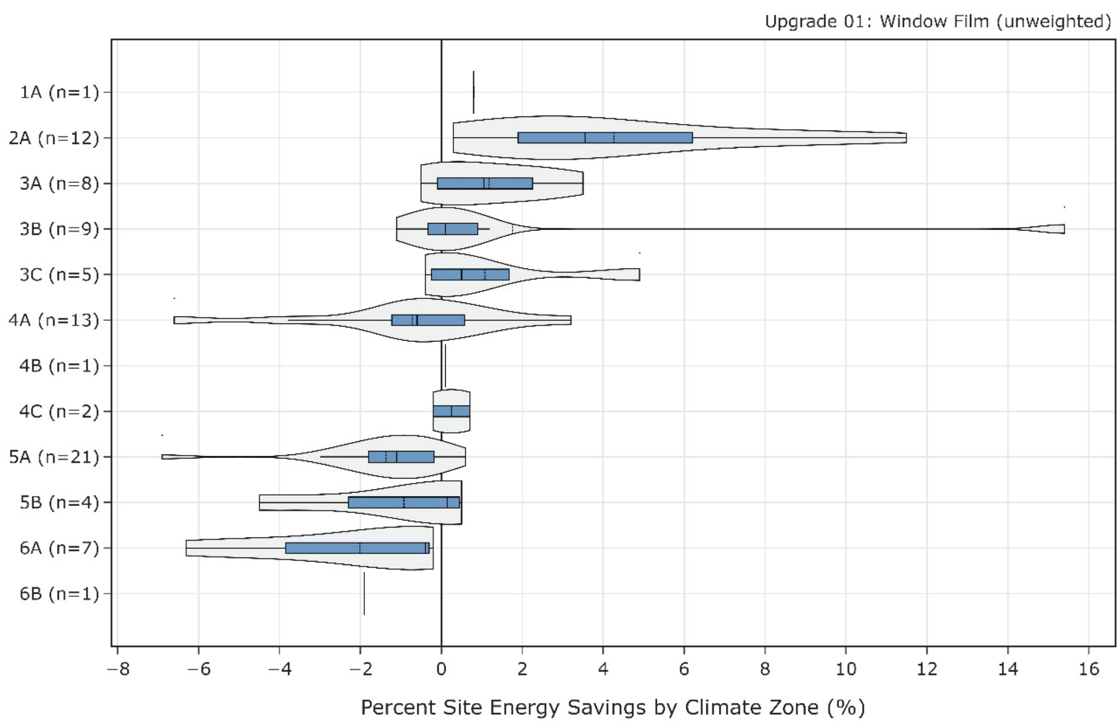

Figure 10. ComStock test results with 100 sample buildings: percent savings by climate zone

5.3 Energy Impacts: 10,000 Building Examples

The window film measure was then tested with 10,000 building samples in ComStock that cover relevant variety across the entire stock characteristics (e.g., climate zone, building type). Figure 11 includes average nominal window performances (SHGC, U-factor, and VLT) of 10,000 building samples between baseline and upgrade scenarios across different climate zones (the number above the bar represents the number of samples/buildings). Similar trends compared to Figure 8 can be seen in Figure 11 from these 10,000 building samples: greatly reduced average SHGC/VLT and slightly reduced average U-factor.

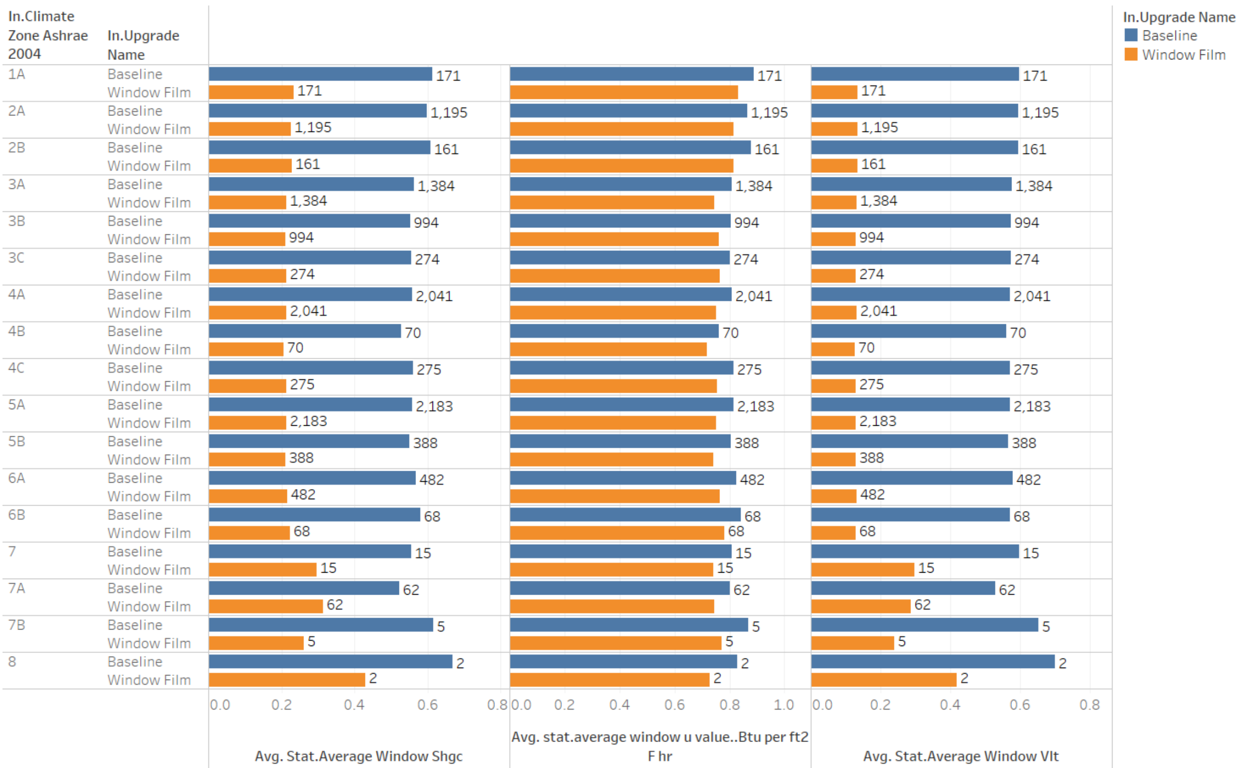

Figure 11. Average window performance of 10,000 building samples: solar heat gain coefficient, U-factor, and visual light transmittance

Figure 12 shows site energy (e.g., heating, cooling, and total) savings across different baseline window type. The color intensity represents the total external window surface area for all sample buildings in each category, and the labels above each bar represent building counts. Overall site energy savings are mostly realized on the single pane window upgrades (as expected), double pane windows' total savings are mostly negative for these samples, and triple pane windows did not receive an upgrade, as shown in the figure.

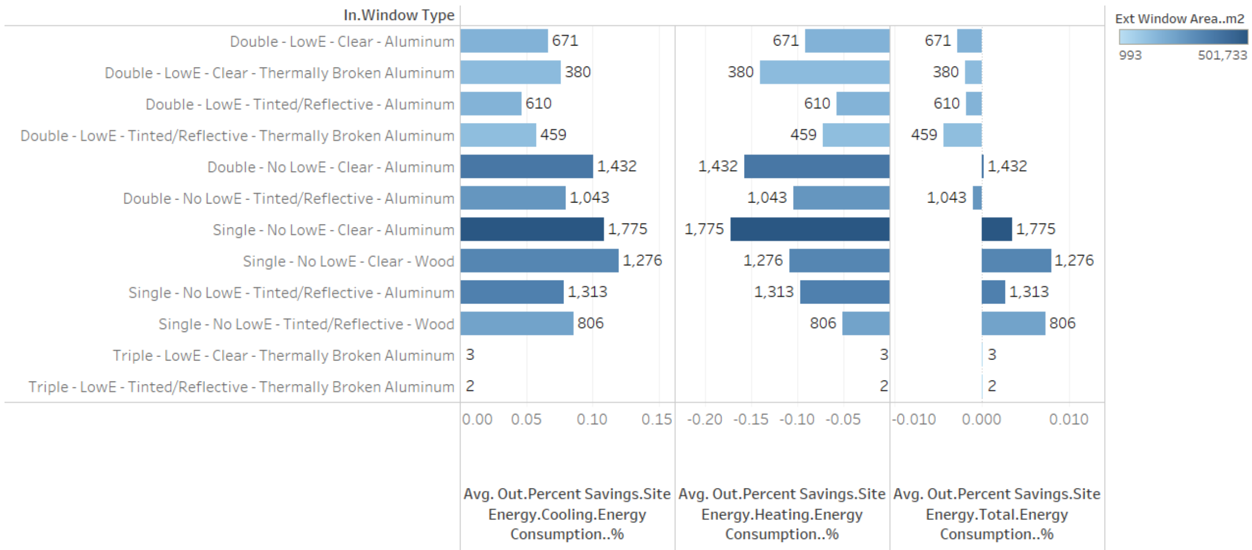

Figure 12. ComStock test results with 10,000 sample buildings: site energy savings by baseline window type

Figure 13 shows distributions of end-use intensity savings for the 10,000 building samples across different end uses. The distributions confirm that end uses related to cooling (e.g., electricity cooling, district cooling, and electricity fans) show positive savings, while end uses related to heating (e.g., natural gas heating and electricity heating) show negative savings.

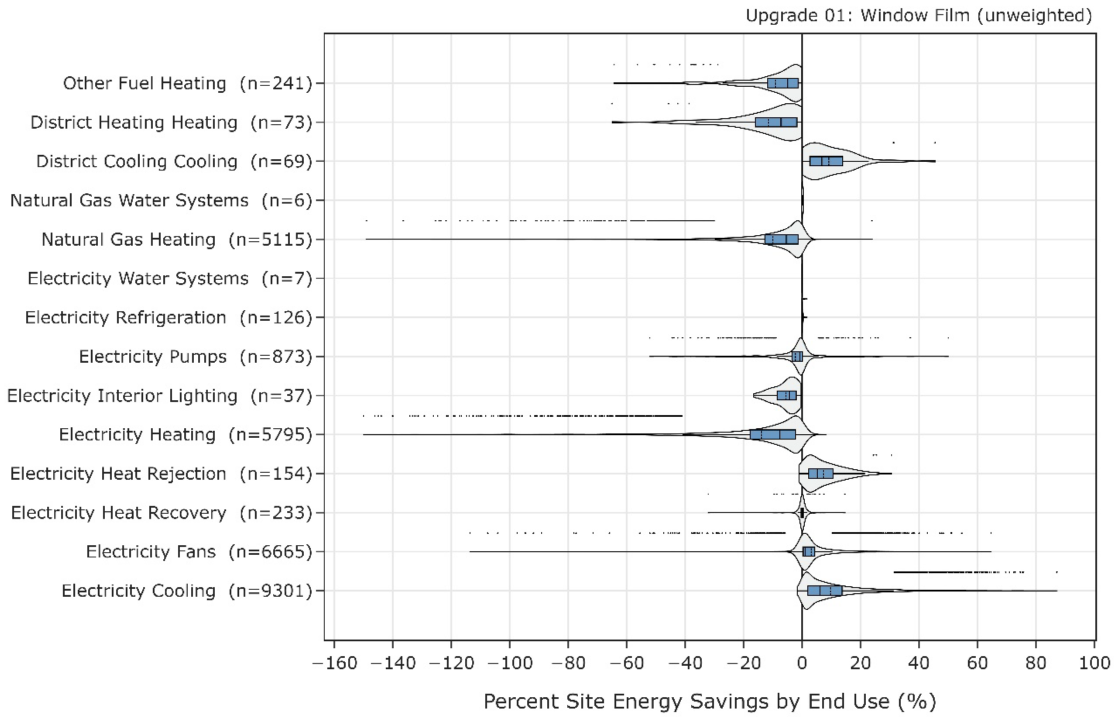

Figure 13. ComStock test results with 10,000 sample buildings: percent savings by end uses

Figure 14 shows distributions of end-use intensity savings for the 10,000 building samples across different climate zones. The distributions confirm the trend of more savings in the hotter climate zones. Climate zones 5 and higher show negative savings (in terms of interquartile range), meaning window films considered in this study are not recommended based on energy savings. In these climates, the benefits of blocking summer solar heat gain are outweighed by the loss of heat gain during winter in cold climates.

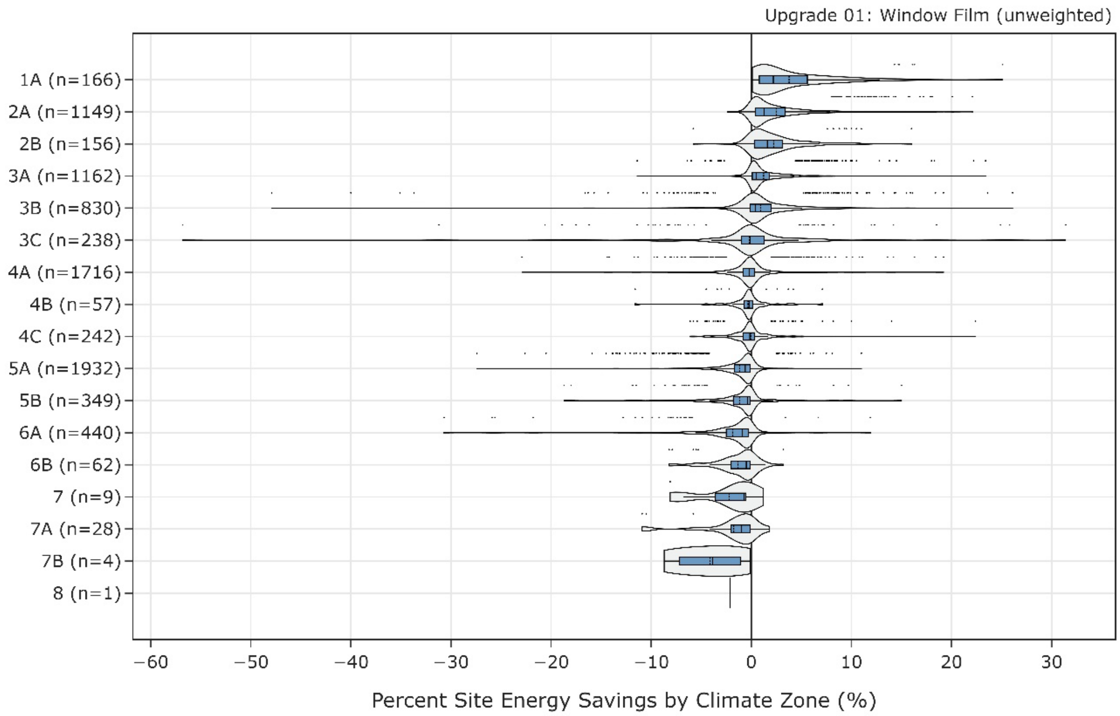

Figure 14. ComStock test results with 10,000 sample buildings: percent savings by climate zone

5.4 Energy Impacts: Full ComStock National Results

This section contains the results of the full ComStock run, which shows the potential impact of the window film measure at the national scale. Figure 15 shows the site energy savings (cooling, heating, and total) in different building segments: Window Type, Climate Zone, and Building Type. The trends that (1) window films in hotter climates and (2) window films on low-performance (e.g., single pane) windows both lead to greater energy savings still stand out in the national results. Since single-pane windows are still more common than double pane windows, the absolute energy savings potential is much higher for single pane windows. Building types such as warehouses, retail stores, primary schools, and hotels contribute more than half of the savings, as they have a large floor area coverage across the stock.

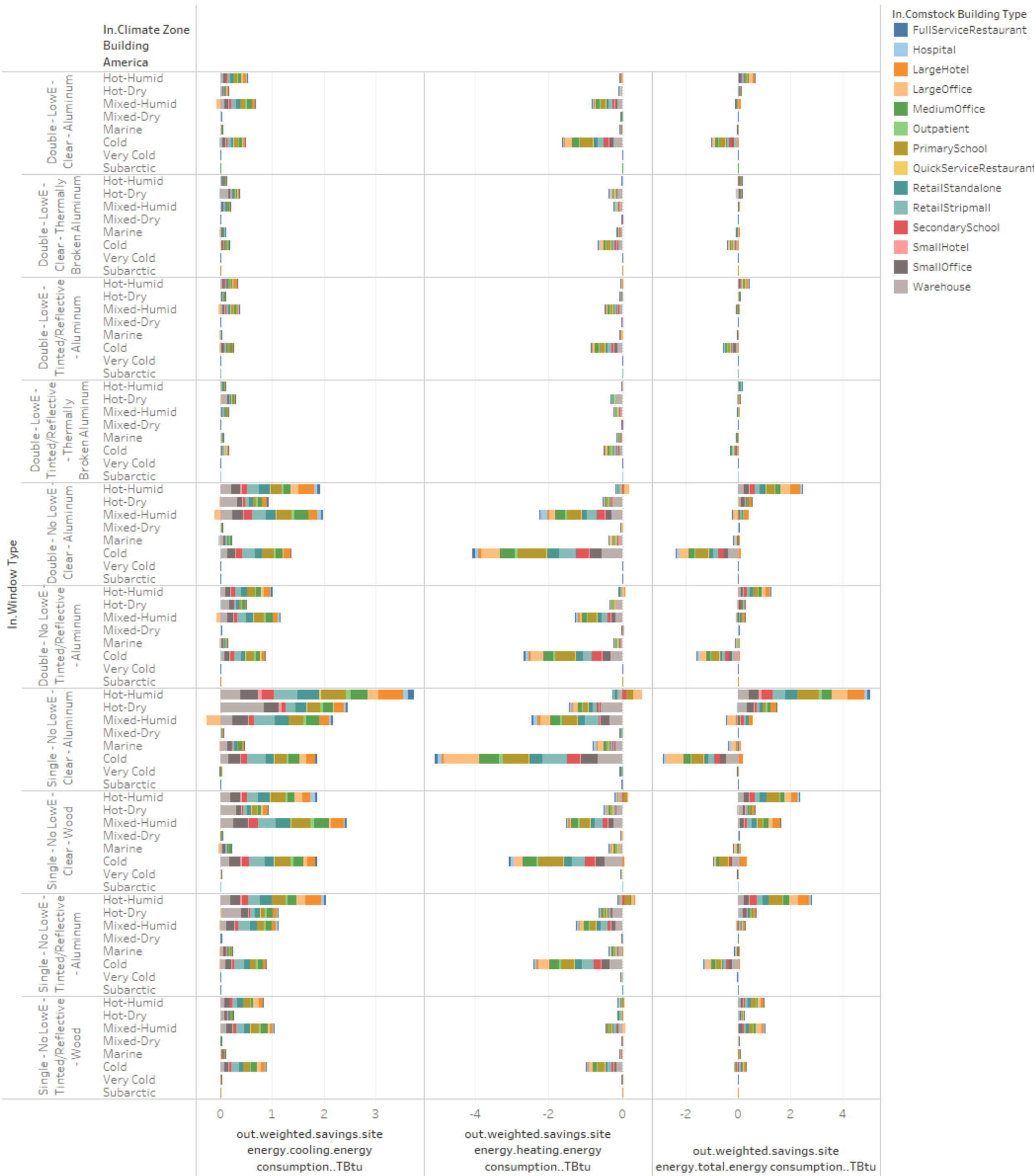

Figure 15. ComStock full national results: aggregated site energy savings on cooling, heating, and total site energy

In hotter regions, such as hot-humid and hot-dry, energy savings are almost guaranteed if the window film is applied to single- or double-pane windows. Buildings typically have varying degrees of internal heat gain as computers, servers, elevators, appliances, people, etc. generate heat to the indoor spaces. The extent of internal heat gains varies depending on the type of the building. As internal heat gains contribute to an increased cooling load, some buildings in colder regions may still require some cooling during the colder months. For this reason, there are also some potential total site energy savings even in colder regions, as shown in Figure 16 (enlarged version of Figure 15 for the bottom row). As can be seen in the figure, buildings such as hotels and retail stores require a relatively higher cooling demand compared to a warehouse in the same region. Therefore, the positive savings are greater in retail and hotel buildings even in cold regions, resulting in positive overall site energy savings from the window film upgrade.

Figure 16. ComStock full national results: Aggregated site energy savings on cooling, heating, and total site energy for single pane window

The overall impact is minimal, but Figure 17 shows the impact of window films on interior lighting energy. There are buildings with daylighting control where the luminance of the light bulb adjusts depending on how bright/dark the indoor space is. The change of illuminance level in the indoor space is due to multiple factors such as sunlight, shading from exterior objects (e.g., trees, neighboring building), window blind position, and window tint level. While factors such as exterior shading and window blinds are not considered in this version of ComStock, sunlight and window tint level are reflected in the simulation results, showing the negative interior lighting energy savings (shown in Figure 17) due to the darkened window by adding a window film. As expected, the scale of negative savings is dependent on the fraction of daylighting control among buildings.

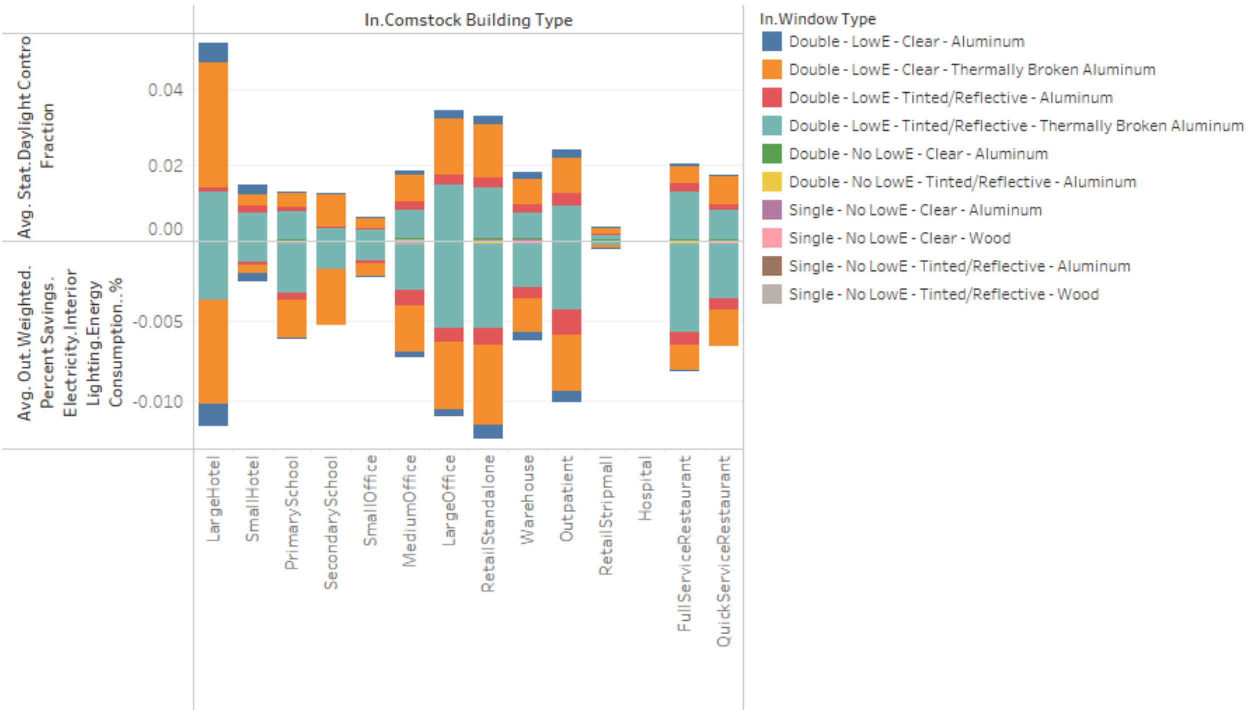

Figure 17. ComStock full national results: Window film impact on interior lighting with daylighting control

While the previous results mostly focused on more detailed segment of buildings for specific climate zones, building types, or end uses, the overall impact of site energy savings from window films on the entire building stock is small (0.25%) as highlighted in Figure 18. As the overall aggregated total savings in relation to the entire building stock are low, some of the end-uses that are not relevant to the window film upgrade are grayed out in the figure to focus only on the relevant end-uses.

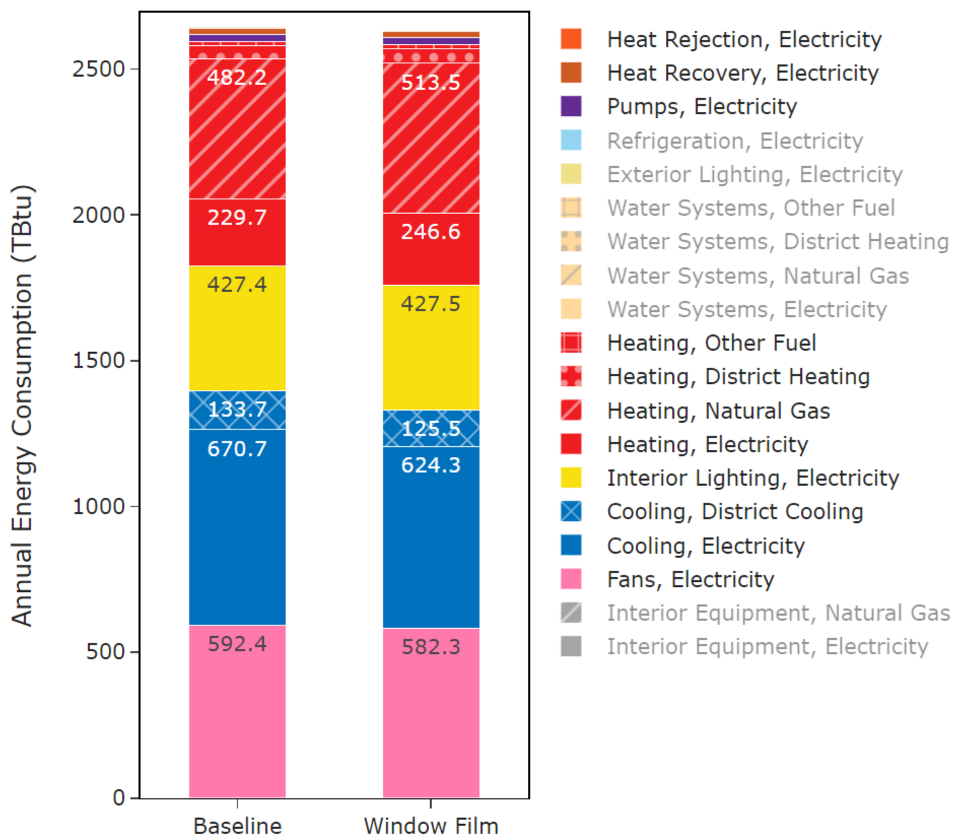

Figure 18. ComStock full national results: aggregated total site energy consumptions

Three electricity grid scenarios are presented to compare the emissions of the ComStock baseline and the HPWH scenario. The choice of grid scenario affects the grid emission factors used in the simulation, which determine the corresponding emissions produced per kilowatt-hour. Two scenarios use the Cambium data set, *Long-Run Marginal Emissions Rate (LRMER) High Renewable Energy Cost 15-Year* and *LRMER Low RE Cost 15-Year*, and the third uses the eGrid data set [4], [5]. All three scenarios vary the emission factors geospatially to reflect the variation in grid resources used to produce electricity across the United States. The Cambium data sets also vary emissions factors seasonally and by time of day. This study does not imply a preference for any particular grid emissions scenario, but other analyses suggest the choice of grid emission scenario can impact results [6]. For on-site fossil fuel combustion emissions, the emission factors listed in Table 5 are used, which are taken from Table 7.1.2(1) of draft ANSI/RESNET/ICCC 301 [7]. To compare total emissions from both on-site fossil fuel consumption and grid electricity generation, emissions from a single electricity grid scenario should be combined with all three on-site fossil fuel emissions.

Table 5. On-Site Fossil Fuel Emissions Factors

Natural gas	147.3 lb/mmbtu (228.0 kg/MWh)
Propane	177.8 lb/mmbtu (182.3 kg/MWh)
Fuel oil	195.9 lb/mmbtu (303.2 kg/MWh)

Figure 19 shows the aggregated GHG emissions based on the assumptions described in the previous paragraph. Similar to the impact of the window film on energy, consumption on GHG is also small, but leads to a positive reduction in electricity consumption.

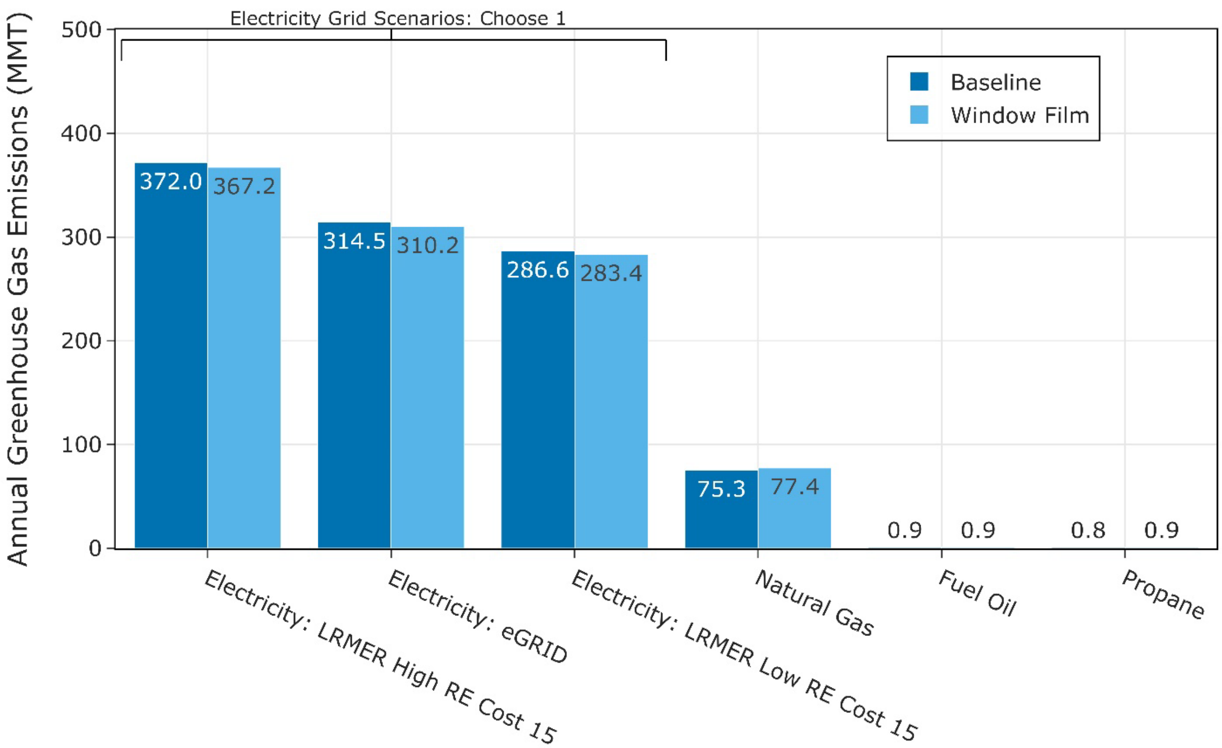

Figure 19. ComStock full national results: aggregated GHG emissions

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