Residential Façade Retrofits

Modeling
NREL Documentation

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December 2021

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Acknowledgments

Thank you to the team at Pacific Northwest National Laboratory (PNNL), including Katherine Cort, Chrissi Antonopoulos, Theresa Gilbride, and Cheryn Metzger, as well as Kohta Ueno at Building Science Corporation (BSC), for support in developing model inputs. The authors also appreciate Chuck Kurnik's (NREL) experience with the weatherization network and bringing contractor experience to the modeling and project overall.

1 Introduction

Older homes, built before 1992 when the DOE's Residential Building Energy Codes program was established, represent approximately 70% of residential building stock in the country and often have significant air leakage, inadequate insulation, and inefficient windows. Windows and walls slowly deteriorate over time; unlike appliances or HVAC equipment, end-of-life for these components is not always obvious. Even when thermal, moisture, and infiltration issues with a home's façade are recognized, the path toward resolving issues is often fraught with technological, financial, and social challenges. Additionally, both problems and solutions will typically vary by the region, climate zone, and the type of construction.

In support of DOE's move toward transformational whole-building upgrades and enclosure solutions, PNNL and NREL partnered and collaborate with leading building science researchers and home performance entities to identify and characterize technical and economic barriers to façade retrofits in an effort to identify market-viable façade solutions and opportunities for an actionable plan to transform the market.

Supplemental to the market characterization study completed by PNNL, this economic analysis adds further granularity into opportunities for energy-efficient residential façade upgrades including integrated enclosure approaches and technologies.

Utilizing NREL's ResStock analysis tool and dataset, an economic analysis was performed for various façade upgrade combinations and strategies for different climate zones. This analysis considers the combined life-cycle cost of re-siding and window upgrades including both home value impacts and recurring bill savings estimates from a ResStock analysis, for varying years of home ownership.

2 Methodology

Overview

The National Renewable Energy Laboratory's (NREL) ResStock™ tool[1] models the residential building stock of the United States. The development team recently completed the End-Use Load Profiles project,[2] which included extensive refinement of the building characteristics used in the tool through calibration against a wide range of datasets, including U.S. Energy Information Administration (EIA) and customer advanced metering infrastructure data. This facade retrofits modeling effort used the ResStock tool, including all the recent refinements.

For this analysis we modeled homes that meet the following criteria:

- Single-family detached
- Occupied year-round
- Built before 1990
- Heat using electricity, natural gas, fuel oil, or propane.

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[1] https://resstock.nrel.gov/

[2] https://www.nrel.gov/buildings/end-use-load-profiles.html

For a full national ResStock run of the 48 contiguous U.S. states, we typically generate a sample of 550,000 homes. Of these, 204,752 single-family detached houses met the above criteria and were modeled. Each of those 204,752 houses had more than 100 individual input characteristics, such as size, vintage, location, wall type, window type, infiltration rate, number of occupants, thermostat setpoints, and so on. These input characteristics are based on structured probability distributions developed using data sources such as the Residential Energy Consumption Survey (RECS), American Community Survey (ACS), American Housing Survey (AHS), and American Time Use Survey (ATUS). We then modeled the characteristics with OpenStudio® and EnergyPlus®, in this case using more than 900 individual Typical Meteorological Year 3 (TMY3) weather data files. Each is meant to represent around 242 actual U.S. houses, for a total of 49.6 million homes.

Retrofits were applied based on each sampled home's existing (baseline) wall and window characteristics. The retrofit upgrade options were specified in collaboration with the full project team and included exterior "polyiso" (polyisocyanurate) insulation (1" or 2"), new triple-pane windows, and/or low-emissivity (low-E) storm windows. The idea was to model these upgrades as if they were done at the time of siding replacement. Accordingly, all insulation upgrades were done in conjunction with siding replacement, but the cost of the siding update was not included in the analysis.

Each insulation upgrade and window upgrade was modeled including a reduction in infiltration (air changes per hour at 50 pascals pressure differential, or ACH50). The infiltration improvements were applied to the conditioned living area and garage area. Other areas (e.g., unconditioned basements, attics, and crawlspaces) were not affected. The infiltration upgrades did not have their own costs or lifetimes, as they are inherent parts of the window and insulation upgrades.

Siding Update

The same siding update logic was applied to all modeled homes, based on the existing siding and no other features. The Pacific Northwest National Laboratory (PNNL) advised NREL on the update logic, which is shown in Table 1. No cost was used for siding updates because the analysis assumes the homeowner has already decided to update the siding.

Table 1. Before and After Siding Upgrades

Existing Siding	Updated Siding
Aluminum, Light	Fiber-Cement, Light
Brick, Light	Stucco, Light
Brick, Medium/Dark	Stucco, Light
Fiber-Cement, Light	Fiber-Cement, Light (no change)
Shingle, Asbestos, Medium	Vinyl, Light
Shingle, Composition, Medium	Vinyl, Light
Stucco, Light	Stucco, Light (no change)
Stucco, Medium/Dark	Stucco, Light
Vinyl, Light	Vinyl, Light (no change)
Wood, Medium/Dark	Fiber-Cement, Light

Insulation Upgrade

Working with the project team, two insulation upgrades were defined for walls, with specifications and cost as shown in Table 2. Costs are based on the high end of the range listed in the National Residential Efficiency Measures Database (REMDB) and are consistent with feedback provided by contractors in a March 2021 workshop.

Table 2. Insulation Upgrade Specifications and Cost

Insulation Upgrade	R-Value	Infiltration Reduction	Cost *per square foot exterior wall area*
1" polyiso exterior continuous insulation	6.5	19%	$1.40[3]
2" polyiso exterior continuous insulation	13	19%	$1.90[4]

These insulation upgrades apply for any home with less than R-19 existing insulation in/on the walls that meets the other criteria for inclusion. Homes with R-19 or higher existing insulation did not receive insulation upgrades but were still eligible for other upgrades (siding, windows). All insulation upgrades included a 30-year lifetime.

We updated the baseline ResStock wall options to better align with desired retrofit specifications. For the final run, the pre-retrofit options are as listed below. The options that meet the upgrade criteria are in bold.

Wood Stud, Uninsulated	**CMU, 6-in Hollow, Uninsulated**	**Brick, 12-in, 3-wythe, Uninsulated**
Wood Stud, R-7	**CMU, 6-in Hollow, R-7**	**Brick, 12-in, 3-wythe, R-7**
Wood Stud, R-11	**CMU, 6-in Hollow, R-11**	**Brick, 12-in, 3-wythe, R-11**
Wood Stud, R-15	**CMU, 6-in Hollow, R-15**	**Brick, 12-in, 3-wythe, R-15**
Wood Stud, R-19	CMU, 6-in Hollow, R-19	Brick, 12-in, 3-wythe, R-19

Windows Upgrade

The project team defined three window upgrades, with specifications and cost as shown in Table 3Table 2. Exterior shading is defined as fixed exterior window shades that block at least 80% of the solar heat gain on sun-struck windows (west-, south- and east-facing windows).[5]

Table 3. Window Upgrade Specifications and Cost

Window Upgrade	Baseline Window	U-factor	SHGC	Infiltration Reduction	Cost *per square foot window area*

[3] https://remdb.nrel.gov/measures.php?gId=12&ctId=410&scId=6547&acId=6552
[4] https://remdb.nrel.gov/measures.php?gId=12&ctId=410&scId=6547&acId=6553
[5] Exterior shades like these are incentivized by some utility companies, such as SRP in Arizona: https://www.srpnet.com/energy/rebates/shadeScreen.aspx

Low-E storm windows	Single, clear, metal	0.57	0.47	15% if added 10% if replacing a clear storm	$14.70[6]
Low-E storm windows	Single, clear, non-metal	0.36	0.46		$14.70
Low-E storm windows	Double, clear, metal	0.49	0.44		$14.70
Low-E storm windows with exterior shading	Single, clear, metal	0.57	0.12		$20.20[7]
Low-E storm windows with exterior shading	Single, clear, non-metal	0.36	0.12		$20.20
Low-E storm windows with exterior shading	Double, clear, metal	0.49	0.11		$20.20
Triple-pane, low-E, insulated, argon, high-gain	Any eligible window	0.18	0.40	30% if replacing a single-pane window Regardless of the presence of clear storm windows before the upgrade 15% if replacing a double-pane window	$46.00[8]

We updated the baseline ResStock window options to better align with desired retrofit specifications. For the final run, the pre-retrofit window types are as listed below (Table 4). Dwelling units with other window types did not receive window upgrades but were still eligible for other upgrades; all window upgrade included a 30-year lifetime.

Table 4. List of Window Upgrade Scenarios

Baseline Window	Low-E Storm Window Upgrade	Triple-Pane Window Upgrade
Single, Clear, Metal	Single, Clear, Metal, Exterior Low-E Storm	Triple, Low-E, Insulated, Argon, High-Gain
Single, Clear, Metal, Exterior Clear Storm	Single, Clear, Metal, Exterior Low-E Storm	Triple, Low-E, Insulated, Argon, High-Gain
Single, Clear, Non-metal	Single, Clear, Non-metal, Exterior Low-E Storm	Triple, Low-E, Insulated, Argon, High-Gain
Single, Clear, Non-metal, Exterior Clear Storm	Single, Clear, Non-metal, Exterior Low-E Storm	Triple, Low-E, Insulated, Argon, High-Gain
Double, Clear, Metal, Air	Double, Clear, Metal, Air Exterior Low-E Storm	Triple, Low-E, Insulated, Argon, High-Gain
Double, Clear, Metal, Air, Exterior Clear Storm	No upgrades applied	

[6] $14.70 per ft^2 is the average of several sources underlying REMDB for professionally installed low-E storm windows and was reviewed by PNNL and DOE collaborators.
[7] $5.50 per ft^2 for exterior shading is based on communication with Jonathan Waterworth of AZ Energy Efficient Home, a company that installs the shades.
[8] $46.00 per ft^2 is based on the average REMDB window replacement labor cost of $21.08 per ft^2 with a 10% increase, plus the average REMDB material cost of $18.31 per ft^2 for double-pane, low-E (high-gain) windows with insulated frames and argon fill, with a $4.50 adder for the additional pane. Coincidentally, $46.00 per ft^2 is also the middle of the range for non-insulated-frame triple-pane windows in the REMDB (https://remdb.nrel.gov/measures.php?gId=16&ctId=190&acId=2077).

Double, Clear, Non-metal, Air	No upgrades applied
Double, Clear, Non-metal, Air, Exterior Clear Storm	No upgrades applied
Double, Low-E, Non-metal, Air, Medium-Gain	No upgrades applied
Triple, Low-E, Non-metal, Air, Low-Gain	No upgrades applied

Infiltration

All baseline infiltration levels received the same percent reductions, which varied based on the insulation and/or window upgrades applicable to the home based on the home's baseline wall and window type.

Figure 1 shows the baseline infiltration options and the percent of homes modeled with each. ResStock's distribution of infiltration is built using data from the Residential Diagnostics Database (ResDB),[9] with dependencies on International Energy Conservation Code (IECC) climate zone, home size, and vintage.

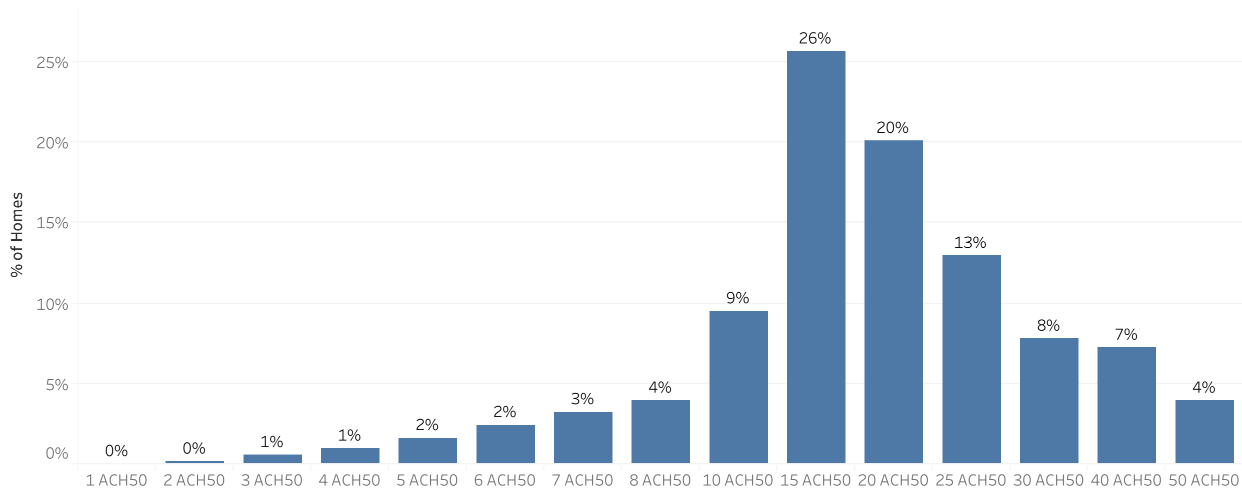

Figure 1. Distribution of envelope air leakage values (ACH50) for the homes modeled in this analysis.

Data derived from http://resdb.lbl.gov.

Model Runs

As shown in

Table 5, we conducted seven model runs, combining the upgrade components described above. These upgrade scenarios were developed in collaboration with the team at PNNL, BSC, and DOE. Of the seven upgrade scenarios, the first three are individual insulation and window component upgrades, and the remaining four are packages of insulation and window upgrades. These four packages were designed to sufficiently cover the parameter space without modeling all possible combinations of upgrades.

[9] http://resdb.lbl.gov

Table 5. List of Upgrade Scenarios

Upgrade Name	Updates and Components Included
1” Insulation	• Siding update • Insulation upgrade: 1” polyiso continuous insulation
Low-E Storms	• Low-E storm windows
Triple-Pane Windows	• Triple-pane windows
1” Insulation and Low-E Storms	• Siding update • Insulation upgrade: 1” polyiso exterior continuous insulation • Windows upgrade: low-e storm windows
1” Insulation and Triple Pane	• Siding update • Insulation upgrade: 1” polyiso exterior continuous insulation • Windows upgrade: triple-pane windows
2” Insulation and Low-E Storms	• Siding update • Insulation upgrade: 2” polyiso exterior continuous insulation • Windows upgrade: low-e storm windows
1” Insulation, Low-E Storms, and Shading	• Siding update • Insulation upgrade: 1” polyiso exterior continuous insulation • Windows upgrade: low-e storm windows and exterior shading

The number of houses that were eligible for each upgrade model run is shown in Figure 2.

		Upgrade Name						
Building America Climate Zone	Vintage Range	1″ Insulation	Low-E Storms	Triple Pane	1″ Insulation & Low-E Storms	1″ Insulation & Triple Pane	2″ Insulation & Low-E Storms	1″ Insulation & Low-E Storms & Shading
Cold & Very Cold	Before 1950	27,799	13,561	13,561	27,972	27,972	27,972	27,972
	1950-1969	28,337	12,546	12,546	28,439	28,439	28,439	28,439
	1970-1989	20,399	8,360	8,360	21,139	21,139	21,139	21,139
Mixed-Humid	Before 1950	14,135	7,414	7,414	14,135	14,135	14,135	14,135
	1950-1969	22,178	11,303	11,303	22,178	22,178	22,178	22,178
	1970-1989	21,892	11,394	11,394	22,370	22,370	22,370	22,370
Marine	Before 1950	2,991	1,659	1,659	2,991	2,991	2,991	2,991
	1950-1969	4,013	2,229	2,229	4,013	4,013	4,013	4,013
	1970-1989	3,726	2,001	2,001	3,778	3,778	3,778	3,778
Hot-Dry & Mixed-Dry	Before 1950	4,272	2,694	2,694	4,272	4,272	4,272	4,272
	1950-1969	9,297	6,091	6,091	9,297	9,297	9,297	9,297
	1970-1989	9,322	6,815	6,815	9,509	9,509	9,509	9,509
Hot-Humid	Before 1950	4,058	3,112	3,112	4,058	4,058	4,058	4,058
	1950-1969	11,264	8,742	8,742	11,264	11,264	11,264	11,264
	1970-1989	15,906	12,729	12,729	16,209	16,209	16,209	16,209
Grand Total		199,589	110,650	110,650	201,624	201,624	201,624	201,624

Figure 2. Number of ResStock representative homes eligible for each of the seven upgrades, aggregated by climate zone and vintage range. Each sample home represents around 242 actual U.S. houses, for a total of 49.6 million homes that were eligible for one or more upgrades in this analysis.

Economic Inputs

We used 2019 energy price data throughout.

Utility Costs

Residential Electricity Costs

We downloaded data from OpenEI's Utility Rate Database[10] to calculate the customer-weighted average fixed monthly electricity charge across all utilities in the database:

$$\frac{\sum \mathit{Fixed\ electric\ charge\ x\ Number\ of\ customers}}{\sum \mathit{Number\ of\ customers}}$$

This came out to approximately $10/customer/month. We downloaded EIA state average residential electricity data[11] including total revenue (in thousands of dollars), total sales (in MWh) and total customers (qty). We then calculated the variable electricity rate for each state, as:

$$\frac{\mathit{Total\ Revenue} - (\mathit{Fixed\ Cost} * \mathit{Number\ of\ Customer})}{\mathit{Total\ Sales}}$$

This resulted in a fixed residential electric utility customer cost of $10/customer/month, which we used throughout the United States, and a per-unit residential electric utility customer rate for each state that varied from 8.7 ¢/kWh in Washington State to 20.4 ¢/kWh in Connecticut.

Residential Natural Gas Costs

For natural gas bill calculations, we used the American Gas Association's value of $11.25/customer/month[12] for the fixed portion of the utility bill (generally referred to as the "customer charge"). We downloaded 2019 EIA data by state on price,[13] consumption,[14] and number of customers,[15] and then calculated the volumetric rate for each state as:

$$\frac{(\mathit{Consumption} * \mathit{Price}) - (\mathit{Fixed\ Cost} * \mathit{Number\ of\ Customer})}{\mathit{Total\ Sales}}$$

The results ranged from $0.43/therm in New Mexico to $1.47/therm in Florida.

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[10] https://openei.org/wiki/Utility_Rate_Database
[11] https://www.eia.gov/electricity/data/state/
[12] American Gas Association. https://www.aga.org/sites/default/files/aga_energy_analysis_-_natural_gas_utility_rate_structure.pdf.
[13] U.S. EIA, "Natural Gas Prices." https://www.eia.gov/dnav/ng/ng_pri_sum_a_epg0_prs_dmcf_a.htm.
[14] U.S. EIA, "Natural Gas Consumption by End Use." https://www.eia.gov/dnav/ng/ng_cons_sum_a_epg0_vrs_mmcf_a.htm.
[15] U.S. EIA, "Number of Natural Gas Consumers." https://www.eia.gov/dnav/ng/ng_cons_num_a_epg0_vn3_count_a.htm.

Residential Fuel Oil and Residential Propane Costs

We downloaded weekly data from the 2018–2019 winter from EIA for residential fuel oil[16] and residential propane,[17] and averaged the data over the available weeks. When state-level data were not available, we used data from the state's Petroleum Administration for Defense Districts (PADD) region. When PADD region data were not available, we used U.S. national average values.

Energy Savings Calculations

We calculated the difference between the total 1-year (annual) energy consumption for each house, upgrade, and fuel. If a house did not receive any part of that upgrade, it was not included. Similarly, if a house was not served by a specific fuel, that fuel was not included. Average energy savings are therefore calculated across houses that received any part of that upgrade that are served in part by that fuel. For example, for the 1" polyiso and low-E storm windows upgrade, houses that were not eligible for the insulation portion of the upgrade (because they had baseline R-19 wall insulation) but were eligible for the low-E storm window option, had their energy savings aggregated with homes that received all portions of the upgrade. This impacts all downstream economic analyses as well. It means that each of the package upgrades shows less energy savings than it would if we had confined the analysis to only homes that were eligible for all portions of the upgrade.

In a small number of cases, energy savings is negative, meaning that total energy consumption for the year was higher after the upgrade than it was in baseline.

Annual Bill Savings Calculations

We multiplied each energy savings result by the appropriate volumetric price based on geography.

Simple Payback Period Calculations

We calculated the simple payback period for each house as the cost of the upgrade divided by the annual bill savings across all fuels.

Net Present Value Calculations

The net present value (NPV) calculation uses the calculated annual bill savings for the first year as the annual bill savings. It also uses the upfront cost of the upgrade, lifetime, analysis period, and real discount rate as inputs. We used an analysis period of 30 years and a real discount rate of 3.4% (5.0% nominal discount rate minus 1.6% inflation).[18] The calculation is then as follows:

$$\sum_{i=0}^{30\,years} \frac{1}{1.034^i}(cost_i - savings_i)$$

[16] U.S. EIA. "No. 2 Distillate Prices by Sales Type." http://www.eia.gov/dnav/pet/pet_pri_dist_a_epd2_prt_dpgal_a.htm

[17] U.S. EIA. "Weekly Heating Oil and Propane Prices (October - March)." https://www.eia.gov/dnav/pet/pet_pri_wfr_a_EPLLPA_PRS_dpgal_w.htm

[18] https://www.energycodes.gov/residential-energy-and-cost-analysis-methodology

Because all the modeled facade retrofits have a modeled lifetime of 30 years, and the analysis period is also 30 years, no replacement cost or residual value component was needed in the calculations.

3 Results, Aggregation, and Visuals

Model Runs

Of the 550,000 residences generated by ResStock, 204,752 single-family detached homes met the criteria for this analysis and were modeled in the baseline, representing 49.5 million houses. Each upgrade run applied to a subset of those 204,752 based on the windows and walls of the house. A previous figure, Figure 2, shows how that broke down by Building America climate zone, vintage, and upgrade.

Individually Run Upgrades Compared to Baseline Features

The *Insulation Only* upgrade applied to 199,589 of the 204,752 baseline houses, representing 48.3 million single-family homes. Figure 3 shows the average site energy saved (MMBtu/yr) and average utility bill savings ($/yr), by Building America climate zone and baseline wall configuration. Data are only included for configuration combinations that included at least 100 houses in the model runs, to avoid including values with high uncertainty.

	Calculation / Building America Climate Zone									
	One Year Energy Savings [mmbtu]					Annual Utility Bill Savings [$]				
Baseline Wall	Cold & Very Cold	Mixed-Humid	Marine	Hot-Dry & Mixed-Dry	Hot-Humid	Cold & Very Cold	Mixed-Humid	Marine	Hot-Dry & Mixed-Dry	Hot-Humid
Wood Stud, Uninsulated	283	408	259	202	400	203	177	95	84	103
Wood Stud, R-7	184	265	158	114	212	95	95	47	44	52
Wood Stud, R-11	178	273	146	110	219	90	87	46	42	52
Wood Stud, R-15	159					82				
CMU, 6-in Hollow, Uninsulated	146	383		295	316	241	141		81	72
CMU, 6-in Hollow, R-7	97	288			156	141	90			35
CMU, 6-in Hollow, R-11	79				148	126				33
Brick, 12-in, 3-wythe, Uninsulated	197	298	221	148	296	138	141	69	54	75

Figure 3. Average (mean) site energy savings (MMBtu/year) and bill savings ($/year) for the 1” insulation upgrade, aggregated by climate zone and baseline wall type. Blanks indicate fewer than 100 samples for a combination of baseline wall and climate zone.

Within each climate zone, the general trend is that houses with less baseline insulation had greater energy savings and greater annual utility bill savings. In the few cases this did not hold true, this is likely due to correlation between parameters like house size, vintage, and baseline wall type. For example, R-11 walls are more likely to be found in newer vintages compared to R-7 walls. Newer vintage homes tend to be larger than older vintages, and therefore absolute energy savings is larger for R-11 baseline walls in some climates.

Both the *Low-E Storms Only* upgrade and *Triple-Pane Windows Only* upgrade applied to 110,650 of the 204,752 baseline houses, representing 26.8 million single-family homes. Figure 4 shows the average energy saved (MMBtu/year) and average utility bill savings ($/year), by

Building America climate zone and baseline window configuration. All configuration combinations eligible included at least 100 houses in the model runs.

		Calculation / Building America Climate Zone									
		One Year Energy Savings [mmbtu]					Annual Utility Bill Savings [$]				
Upgrade Name	Baseline Window	Cold & Very Cold	Mixed-Humid	Marine	Hot-Dry & Mixed-Dry	Hot-Humid	Cold & Very Cold	Mixed-Humid	Marine	Hot-Dry & Mixed-Dry	Hot-Humid
Low-E Storms	Single, Clear, Metal	153	230	75	139	243	81	74	26	45	56
	Single, Clear, Metal, Exterior Clear Storm	64	95	27	45	103	36	34	10	16	24
	Single, Clear, Non-metal	144	209	113	94	210	92	84	40	37	52
	Single, Clear, Non-metal, Exterior Clear Storm	61	89	37	38	95	39	37	15	14	24
	Double, Clear, Metal, Air	118	187	67	104	205	65	63	23	35	48
Triple Pane	Single, Clear, Metal	292	426	164	217	411	168	148	60	76	98
	Single, Clear, Metal, Exterior Clear Storm	228	319	106	130	314	136	120	41	51	77
	Single, Clear, Non-metal	234	341	189	141	338	154	141	67	57	84
	Single, Clear, Non-metal, Exterior Clear Storm	169	246	112	89	250	113	109	46	36	64
	Double, Clear, Metal, Air	183	283	126	145	288	107	100	45	53	69

Figure 4. Average (mean) site energy savings (MMBtu/year) and bill savings ($/year) for the two window upgrades, aggregated by climate zone and baseline window type.

Energy Savings

Average changes in total annual site energy consumption across all fuels are presented in Figure 5 (MMBtu/year) and Figure 6 (percent), alongside the standard deviation (sd), which indicates the distribution across the diversity of housing stock characteristics (e.g., thermostat setpoints). Averages are used rather than medians to allow the values to be aggregated in order to calculate total energy savings across a population of houses. These values are computed across all houses to which any part of the upgrade model run was applied.[19] Houses to which no part of a given upgrade model run are applied are not included in the calculations for that specific upgrade model run. Positive values are energy *savings*; the few instances of negative values from individual models, as seen in the histograms in Figure 7, are increases in energy consumption. In the figure, darker background colors indicate greater average energy savings. These values include savings across all four fuel types considered in the analysis: electricity, natural gas, propane, and fuel oil.

[19] For example, a house with R-19 insulation and single-pane windows would have the window upgrade portion of an upgrade package applied, but not the insulation portion.

Building America Climate Zone	Vintage Range	Upgrade Name 1″ Insulation	Low-E Storms	Triple Pane	1″ Insulation & Low-E Storms	1″ Insulation & Triple Pane	2″ Insulation & Low-E Storms	1″ Insulation & Low-E Storms & Shading
Cold & Very Cold	Before 1950	38.6 (sd 21.5)	17.2 (sd 11.1)	31.0 (sd 20.1)	46.0 (sd 26.8)	52.4 (sd 33.1)	52.9 (sd 30.3)	43.7 (sd 25.2)
	1950-1969	32.3 (sd 17.5)	14.1 (sd 9.2)	25.8 (sd 16.7)	37.8 (sd 21.6)	42.7 (sd 26.6)	43.6 (sd 24.4)	36.2 (sd 20.4)
	1970-1989	17.8 (sd 10.6)	13.1 (sd 9.3)	24.2 (sd 17.1)	21.9 (sd 14.7)	26.3 (sd 20.2)	25.3 (sd 16.3)	20.4 (sd 13.5)
Mixed-Humid	Before 1950	30.9 (sd 19.9)	12.6 (sd 9.2)	23.1 (sd 16.8)	36.9 (sd 24.6)	42.0 (sd 29.8)	42.3 (sd 27.7)	35.2 (sd 23.1)
	1950-1969	26.0 (sd 16.2)	10.3 (sd 7.6)	19.1 (sd 14.0)	30.8 (sd 19.8)	34.9 (sd 24.1)	35.2 (sd 22.3)	29.6 (sd 18.7)
	1970-1989	14.5 (sd 10.5)	8.9 (sd 6.4)	16.5 (sd 12.2)	18.3 (sd 13.4)	22.0 (sd 17.3)	20.9 (sd 15.0)	17.5 (sd 12.5)
Marine	Before 1950	17.6 (sd 14.0)	6.0 (sd 6.2)	11.6 (sd 11.2)	20.5 (sd 16.9)	23.3 (sd 20.1)	23.8 (sd 19.4)	18.6 (sd 15.4)
	1950-1969	14.5 (sd 11.9)	4.4 (sd 4.4)	8.6 (sd 8.3)	16.6 (sd 13.7)	18.8 (sd 15.9)	19.3 (sd 15.8)	15.2 (sd 12.8)
	1970-1989	10.1 (sd 9.3)	4.2 (sd 4.2)	8.7 (sd 8.0)	12.0 (sd 10.7)	14.2 (sd 12.9)	14.0 (sd 12.4)	10.4 (sd 10.1)
Hot-Dry & Mixed-Dry	Before 1950	10.8 (sd 9.5)	3.9 (sd 3.8)	7.2 (sd 7.0)	12.9 (sd 11.5)	14.8 (sd 13.8)	14.9 (sd 13.2)	12.0 (sd 10.7)
	1950-1969	11.0 (sd 9.1)	3.9 (sd 3.6)	7.2 (sd 6.6)	13.2 (sd 11.2)	15.1 (sd 13.4)	15.1 (sd 12.8)	12.5 (sd 10.4)
	1970-1989	7.3 (sd 7.3)	4.4 (sd 3.8)	8.0 (sd 7.3)	10.1 (sd 9.3)	12.5 (sd 11.9)	11.5 (sd 10.6)	9.7 (sd 8.7)
Hot-Humid	Before 1950	12.9 (sd 9.3)	6.1 (sd 4.4)	11.0 (sd 8.2)	17.3 (sd 12.2)	20.6 (sd 15.2)	19.5 (sd 13.7)	17.5 (sd 11.6)
	1950-1969	10.8 (sd 8.1)	5.1 (sd 3.7)	9.0 (sd 7.0)	14.4 (sd 10.5)	17.2 (sd 13.2)	16.2 (sd 11.8)	14.8 (sd 10.0)
	1970-1989	6.7 (sd 6.0)	5.2 (sd 3.8)	8.9 (sd 7.2)	10.3 (sd 8.4)	13.0 (sd 11.1)	11.4 (sd 9.3)	11.0 (sd 8.2)

Figure 5. Average (mean) and standard deviation of annual site energy savings (MMBtu/year) for the seven upgrades, aggregated by climate zone and vintage range.

Building America Climate Zone	Vintage Range	Upgrade Name 1″ Insulation	Low-E Storms	Triple Pane	1″ Insulation & Low-E Storms	1″ Insulation & Triple Pane	2″ Insulation & Low-E Storms	1″ Insulation & Low-E Storms & Shading
Cold & Very Cold	Before 1950	20.9% (sd 4.9%)	8.9% (sd 3.1%)	16.2% (sd 5.3%)	24.8% (sd 6.3%)	28.1% (sd 9.0%)	28.6% (sd 7.1%)	23.5% (sd 5.7%)
	1950-1969	20.0% (sd 4.7%)	8.4% (sd 2.9%)	15.3% (sd 5.2%)	23.3% (sd 5.9%)	26.2% (sd 8.5%)	26.9% (sd 6.6%)	22.3% (sd 5.4%)
	1970-1989	12.6% (sd 3.2%)	8.9% (sd 3.3%)	16.5% (sd 5.9%)	15.4% (sd 5.3%)	18.4% (sd 8.5%)	17.9% (sd 5.7%)	14.3% (sd 4.7%)
Mixed-Humid	Before 1950	19.7% (sd 4.6%)	7.9% (sd 2.7%)	14.4% (sd 4.9%)	23.4% (sd 6.1%)	26.6% (sd 8.6%)	26.9% (sd 6.7%)	22.4% (sd 5.4%)
	1950-1969	18.7% (sd 4.3%)	7.3% (sd 2.5%)	13.5% (sd 4.8%)	22.1% (sd 5.6%)	25.0% (sd 8.0%)	25.3% (sd 6.2%)	21.3% (sd 5.1%)
	1970-1989	12.3% (sd 4.8%)	7.6% (sd 2.9%)	14.0% (sd 5.5%)	15.6% (sd 6.2%)	18.7% (sd 8.6%)	17.8% (sd 6.8%)	14.9% (sd 5.7%)
Marine	Before 1950	17.5% (sd 6.7%)	5.8% (sd 3.2%)	11.3% (sd 5.5%)	20.3% (sd 8.0%)	23.0% (sd 10.0%)	23.5% (sd 9.2%)	18.3% (sd 7.4%)
	1950-1969	15.8% (sd 6.4%)	4.9% (sd 3.0%)	9.6% (sd 5.3%)	18.1% (sd 7.5%)	20.4% (sd 9.2%)	21.0% (sd 8.7%)	16.4% (sd 7.1%)
	1970-1989	11.4% (sd 5.8%)	5.0% (sd 3.3%)	10.3% (sd 6.0%)	13.6% (sd 6.9%)	16.2% (sd 8.8%)	15.9% (sd 7.9%)	11.5% (sd 6.8%)
Hot-Dry & Mixed-Dry	Before 1950	13.1% (sd 6.7%)	4.6% (sd 2.9%)	8.6% (sd 5.1%)	15.6% (sd 8.1%)	17.8% (sd 9.8%)	18.0% (sd 9.3%)	14.5% (sd 7.5%)
	1950-1969	13.5% (sd 6.7%)	4.7% (sd 2.8%)	8.7% (sd 5.0%)	16.2% (sd 8.0%)	18.4% (sd 9.8%)	18.5% (sd 9.2%)	15.3% (sd 7.5%)
	1970-1989	9.0% (sd 5.7%)	5.5% (sd 3.1%)	10.0% (sd 5.6%)	12.4% (sd 7.0%)	15.3% (sd 9.2%)	14.2% (sd 8.0%)	12.0% (sd 7.0%)
Hot-Humid	Before 1950	13.2% (sd 5.1%)	6.4% (sd 2.4%)	11.3% (sd 4.6%)	17.8% (sd 6.4%)	21.1% (sd 8.4%)	20.1% (sd 7.2%)	18.3% (sd 6.1%)
	1950-1969	12.1% (sd 5.1%)	5.9% (sd 2.4%)	10.2% (sd 4.5%)	16.4% (sd 6.3%)	19.4% (sd 8.3%)	18.4% (sd 7.1%)	17.1% (sd 6.0%)
	1970-1989	8.0% (sd 4.5%)	6.4% (sd 2.7%)	10.8% (sd 5.1%)	12.5% (sd 5.9%)	15.6% (sd 8.0%)	13.8% (sd 6.5%)	13.6% (sd 6.0%)

Figure 6. Average (mean) and standard deviation of percent site energy savings for the seven upgrades, aggregated by climate zone and vintage range.

Figure 5 and Figure 6 show greatest average energy savings in the Cold & Very Cold and Mixed-Humid climate zones. Due to the nature of ResStock, this locational variation includes both the impacts of different weather and the differences in the housing stock in each climate zone. The figures also show greater energy savings for older homes. The upgrade model run of 2" of insulation with low-E storms generally shows the greatest energy savings, though not by a wide margin. In some climate zone and vintage combinations, the 1" insulation with triple pane or the 1" insulation with low-E storms and shading option shows the greatest energy savings. In every climate zone and vintage range combination, the low-E storms stand-alone option shows the lowest energy savings.

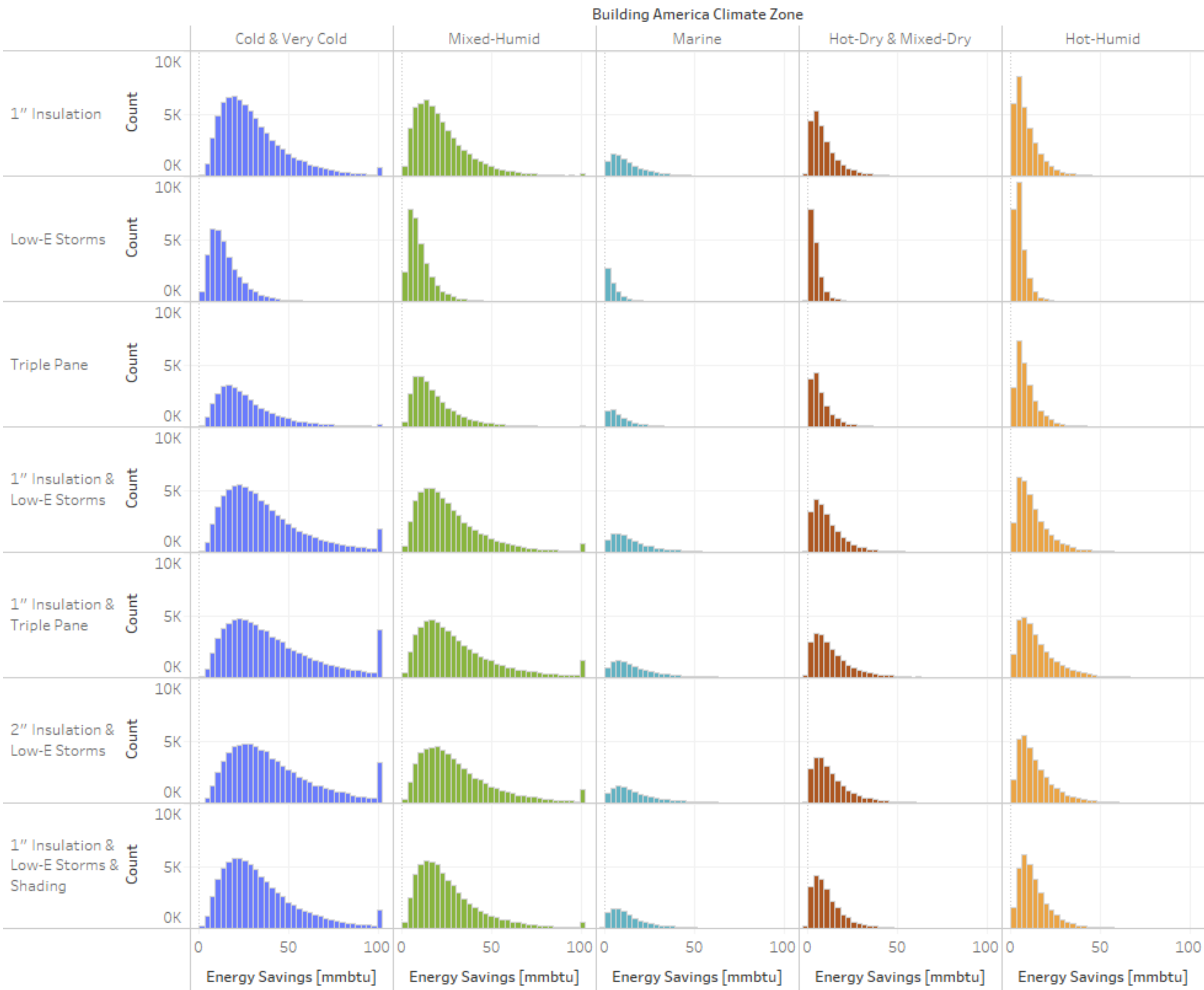

Figure 7. Distributions of annual energy savings (MMBtu/year) for all seven upgrades, separated by climate zone. The histograms have a bin size of 3 MMBtu/yr, an overflow bin for values 99 MMBtu/yr and over, and an underflow bin for values below -5 MMBtu/yr (negative values indicate an increase in energy use after the upgrade).

The histograms in Figure 7 show some of the story behind these averages. We see many homes with savings of under 50 MMBtu/yr, a few homes with negative savings, and long tails of high energy savings as demonstrated by the high house counts in some of the 99+ MMBtu/yr bins. The distributions of the upgrade package runs in the Cold & Very Cold climate zone peak around 21 to 27 MMBtu/yr. At the other end of the spectrum, the distributions for annual bill savings for the upgrade packages in Hot-Dry & Mixed-Dry and Hot-Humid climate zones peak between 3 and 9 MMBtu/yr.

Bill Savings

Annual bill savings are presented as averages, alongside the standard deviation (sd), in Figure 8. Averages are used rather than medians to allow the values to be aggregated in order to calculate total bill savings across a population. Averages are over only those homes to which some portion of the upgrade applied. The darker the background color, the greater the annual bill savings.

Building America Climate Zone	Vintage Range	Upgrade Name: 1″ Insulation	Low-E Storms	Triple Pane	1″ Insulation & Low-E Storms	1″ Insulation & Triple Pane	2″ Insulation & Low-E Storms	1″ Insulation & Low-E Storms & Shading
Cold & Very Cold	Before 1950	$489 (sd 413)	$222 (sd 191)	$394 (sd 347)	$586 (sd 504)	$665 (sd 600)	$674 (sd 576)	$570 (sd 480)
	1950-1969	$407 (sd 347)	$181 (sd 158)	$323 (sd 288)	$479 (sd 414)	$539 (sd 488)	$552 (sd 474)	$469 (sd 397)
	1970-1989	$248 (sd 206)	$192 (sd 168)	$348 (sd 316)	$310 (sd 276)	$370 (sd 365)	$358 (sd 311)	$297 (sd 256)
Mixed-Humid	Before 1950	$465 (sd 350)	$201 (sd 155)	$356 (sd 277)	$563 (sd 428)	$638 (sd 509)	$644 (sd 486)	$555 (sd 410)
	1950-1969	$414 (sd 291)	$174 (sd 130)	$311 (sd 238)	$496 (sd 354)	$561 (sd 425)	$568 (sd 402)	$491 (sd 340)
	1970-1989	$278 (sd 215)	$181 (sd 128)	$323 (sd 242)	$357 (sd 272)	$426 (sd 346)	$408 (sd 307)	$353 (sd 259)
Marine	Before 1950	$257 (sd 246)	$91 (sd 107)	$172 (sd 193)	$301 (sd 296)	$341 (sd 350)	$349 (sd 341)	$277 (sd 267)
	1950-1969	$217 (sd 204)	$71 (sd 82)	$132 (sd 148)	$251 (sd 239)	$282 (sd 278)	$291 (sd 276)	$237 (sd 225)
	1970-1989	$159 (sd 160)	$73 (sd 77)	$143 (sd 149)	$191 (sd 188)	$226 (sd 229)	$224 (sd 218)	$172 (sd 176)
Hot-Dry & Mixed-Dry	Before 1950	$191 (sd 216)	$80 (sd 91)	$133 (sd 157)	$238 (sd 268)	$266 (sd 313)	$273 (sd 308)	$248 (sd 269)
	1950-1969	$201 (sd 215)	$84 (sd 84)	$136 (sd 146)	$252 (sd 262)	$281 (sd 306)	$288 (sd 301)	$267 (sd 265)
	1970-1989	$148 (sd 178)	$114 (sd 106)	$181 (sd 181)	$222 (sd 233)	$266 (sd 291)	$252 (sd 265)	$250 (sd 244)
Hot-Humid	Before 1950	$263 (sd 192)	$137 (sd 97)	$232 (sd 171)	$362 (sd 256)	$428 (sd 317)	$407 (sd 289)	$390 (sd 261)
	1950-1969	$228 (sd 162)	$119 (sd 79)	$200 (sd 143)	$315 (sd 215)	$372 (sd 268)	$353 (sd 242)	$343 (sd 219)
	1970-1989	$162 (sd 140)	$135 (sd 96)	$223 (sd 173)	$259 (sd 200)	$323 (sd 264)	$286 (sd 222)	$291 (sd 208)

Figure 8. Average (mean) and standard deviation of annual bill savings for the seven upgrades, aggregated by climate zone and vintage range.

These figures show greatest average utility bill savings in the Cold & Very Cold and Mixed-Humid climate zones; these are the same areas that showed the greatest energy savings. However, the Hot-Humid climate zone shows high average utility bill savings as well, much higher than would be expected from its energy savings relative to the other climate zones. This is likely due primarily to the type of energy being saved—many more homes heat with electricity in the Hot-Humid climate zone than in most of the other climate zones.

As seen in the histograms in Figure 9, in the Cold & Very Cold climate zone, the distribution peaks range from $50–$100 for low-E storms to $200–$250 for all of the upgrade packages. There is also a very long tail, as evidenced by the height of the $1,500+ bin. In the Mixed-Humid climate zone, the package that includes 2” insulation peaks even higher, at $250–$300. At the other end of the spectrum, no distribution peaks above $100 in the Hot-Dry & Mixed-Dry climate zone.

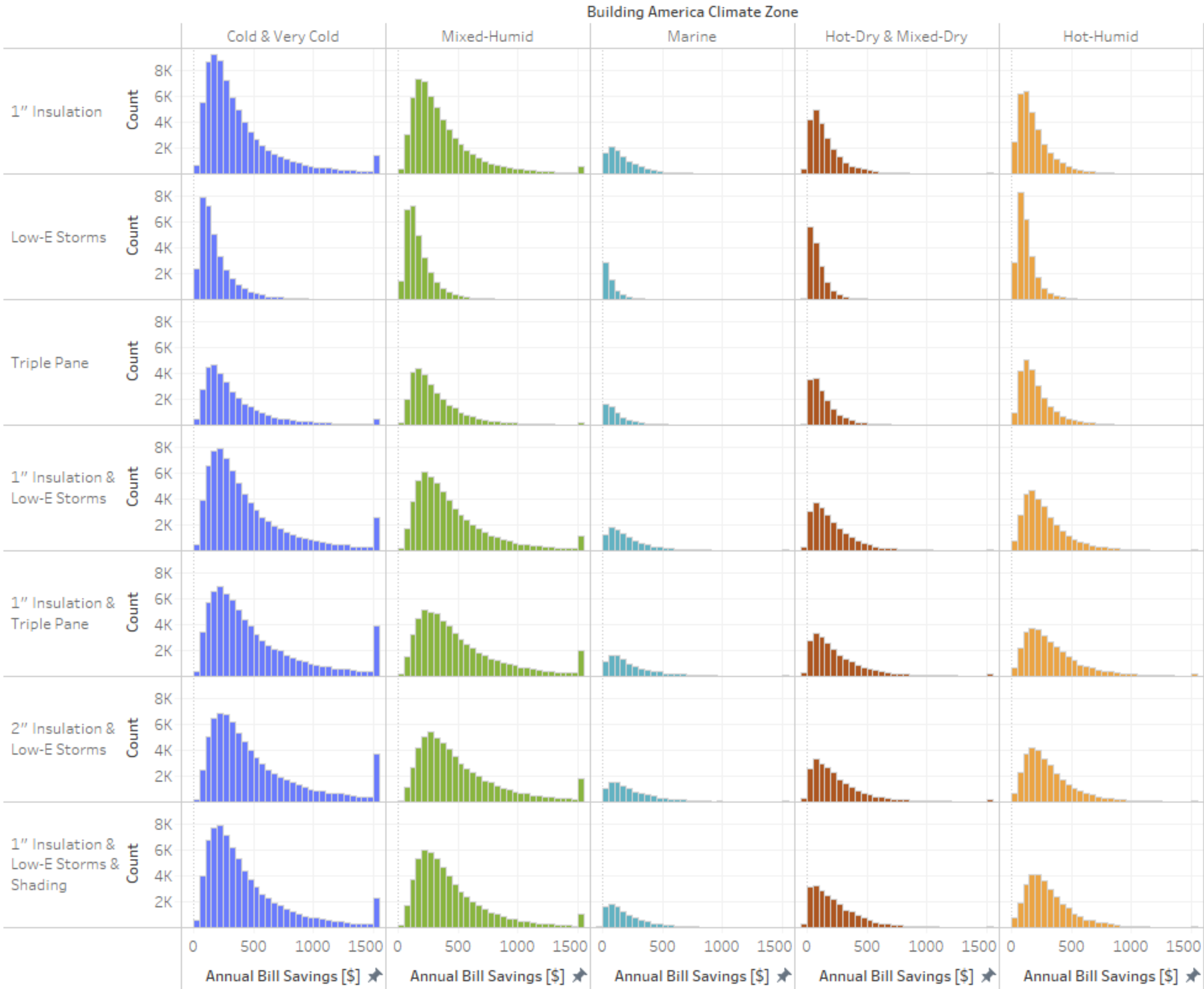

Figure 9. Distributions of annual bill savings ($/year) for all seven upgrades, separated by climate zone. The histograms use a bin size of $50, an overflow bin for values $1,500 or higher, and an underflow bin for values -$50 or below.

Simple Payback Period

Simple payback periods (SPP) are presented as medians,[20] alongside the standard deviation (sd), in Figure 10. The darker the background color in the figure, the lower the simple payback period.

Median SPP [yrs]

Building America Climate Zone	Vintage Range	1" Insulation	Low-E Storms	Triple Pane	1" Insulation & Low-E Storms	1" Insulation & Triple Pane	2" Insulation & Low-E Storms	1" Insulation & Low-E Storms & Shading
Cold & Very Cold	Before 1950	7 (sd 5)	16 (sd 71)	29 (sd 24)	8 (sd 6)	10 (sd 11)	9 (sd 7)	9 (sd 940)
	1950-1969	8 (sd 6)	17 (sd 16)	30 (sd 26)	9 (sd 7)	10 (sd 11)	10 (sd 7)	9 (sd 12)
	1970-1989	14 (sd 13)	17 (sd 20)	30 (sd 27)	15 (sd 14)	18 (sd 17)	17 (sd 15)	17 (sd 164)
Mixed-Humid	Before 1950	7 (sd 4)	17 (sd 13)	31 (sd 21)	8 (sd 5)	11 (sd 10)	9 (sd 5)	9 (sd 7)
	1950-1969	7 (sd 4)	17 (sd 13)	31 (sd 22)	9 (sd 5)	11 (sd 10)	10 (sd 5)	10 (sd 6)
	1970-1989	13 (sd 10)	18 (sd 12)	32 (sd 21)	14 (sd 10)	18 (sd 15)	15 (sd 10)	16 (sd 86)
Marine	Before 1950	13 (sd 39)	43 (sd 441)	73 (sd 217)	17 (sd 53)	23 (sd 88)	18 (sd 68)	20 (sd 12,391)
	1950-1969	15 (sd 473)	49 (sd 2,360)	87 (sd 363)	20 (sd 477)	27 (sd 489)	21 (sd 84)	22 (sd 1,185)
	1970-1989	25 (sd 196)	49 (sd 2,463)	82 (sd 426)	29 (sd 226)	36 (sd 7,244)	31 (sd 220)	31 (sd 2,591)
Hot-Dry & Mixed-Dry	Before 1950	18 (sd 1,151)	45 (sd 2,317)	91 (sd 921)	24 (sd 1,174)	36 (sd 9,401)	25 (sd 1,558)	24 (sd 2,749)
	1950-1969	16 (sd 769)	37 (sd 1,547)	77 (sd 2,191)	21 (sd 718)	32 (sd 1,444)	22 (sd 2,004)	21 (sd 1,244)
	1970-1989	28 (sd 167,360,772)	28 (sd 73,394,631)	60 (sd 5,979,035,812)	28 (sd 76,935,689)	41 (sd 1,339,312,756)	30 (sd 150,420,878)	26 (sd 103,341,100)
Hot-Humid	Before 1950	11 (sd 16)	24 (sd 54)	45 (sd 65)	15 (sd 25)	24 (sd 43)	16 (sd 31)	16 (sd 35)
	1950-1969	13 (sd 869)	24 (sd 400)	47 (sd 274)	16 (sd 873)	26 (sd 885)	18 (sd 1,615)	17 (sd 930)
	1970-1989	23 (sd 240)	24 (sd 303)	47 (sd 230)	23 (sd 243)	35 (sd 269)	26 (sd 344)	24 (sd 385)

(Column group heading: Upgrade Name)

Figure 10. Median and standard deviation of simple payback period for the seven upgrades, aggregated by climate zone and vintage range. Note: color scale is capped at 30 years.

Maximum median SPP in Figure 10 is 41 years for the packages of upgrades, but as high as 91 years for the stand-alone triple-pane upgrade. There is considerable range among the SPP for individual houses as evidenced by both the standard deviations and the histograms. Based on median SPP values, the 1" insulation measure performs the best of the seven scenarios, with median SPP around 7 years for homes built before 1970 in the Cold and Mixed-Humid climate zones. The four packages that include wall insulation also perform well, with median SPP values in the 8- to 11-year range for homes built before 1970 in the Cold and Mixed-Humid climate zones.

[20] Medians are used rather than averages due to the extreme sensitivity of the SPP metric to outliers. For example, a relatively typical example house in our modeling results saw an 8.2 MMBtu/yr annual energy savings for the insulation-only upgrade and a $260 annual bill savings, which led to a simple payback period of 7.2 years. Meanwhile, looking at the same upgrade, a single house in Arizona in the Hot-Dry climate with no air conditioning and a low heating setpoint (60°F) showed very nearly no change in energy consumption—just a -1.4×10^{-8} MMBtu/yr increase and an accordingly small change in utility bills of a tiny fraction of a penny ($-\$1.23 \times 10^{-7}$). This house is clearly not a good candidate for this upgrade, and there are not too many like it in the dataset, but it does meet the requirements laid out by the project team and it greatly distorts some of the aggregations. Looking at the insulation-only upgrade alone, 422 sample houses (2.1%) have simple payback periods below 0, and 391 (2.0%) have simple payback periods over 500. However, despite the small share of these outliers, the extreme nature of some of them make metrics such as average unusable.

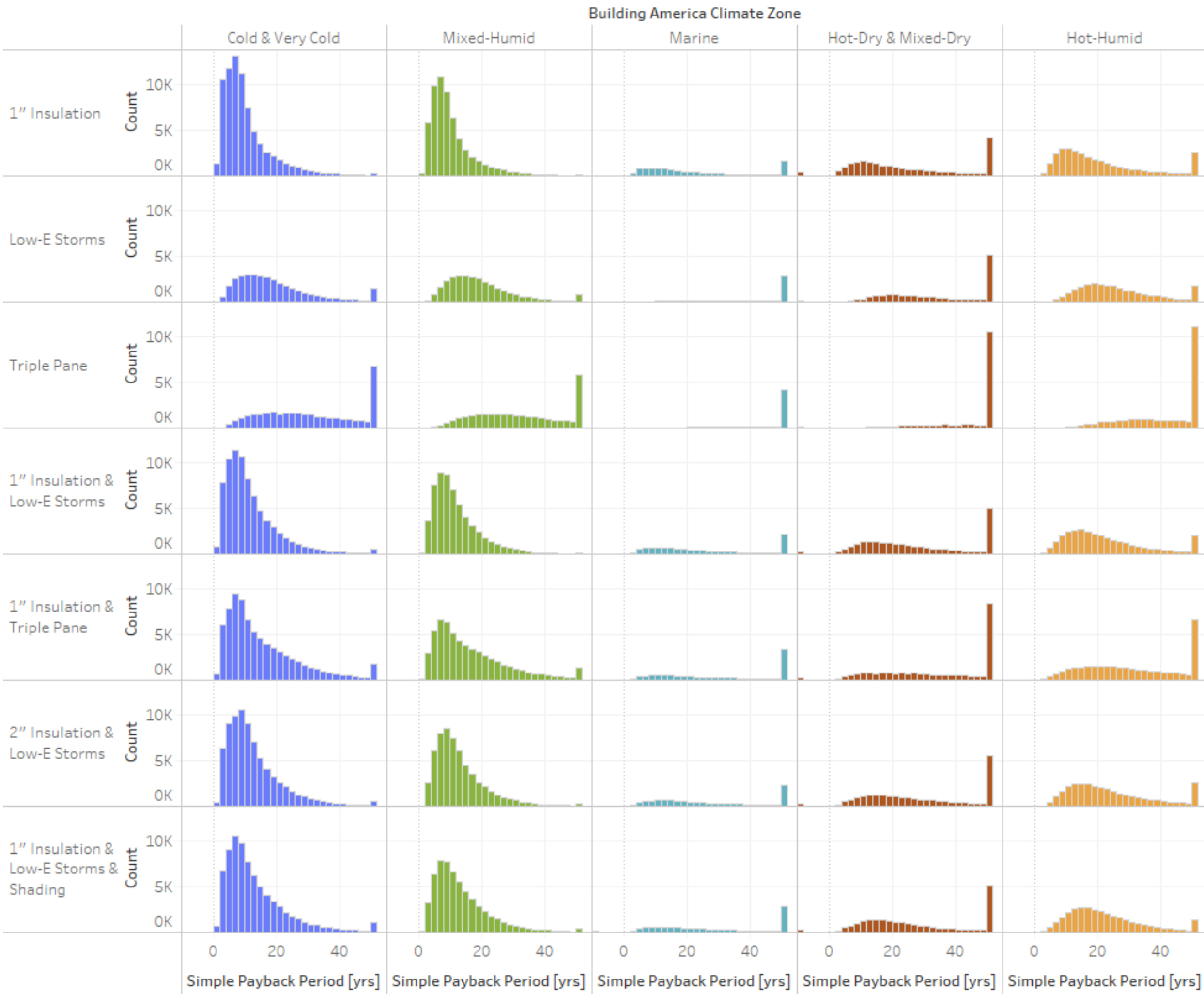

Figure 11. Distributions of simple payback period for all seven upgrades, separated by climate zone. The histograms have a bin size of two years with an overflow bin for 50 years and above, and an underflow bin for -10 years and below.

Figure 11 shows how the simple payback periods are distributed in each climate zone. Although every distribution of upgrade package SPP shown peaks below 20 years, the tails on many of the distributions are very, very long. Every upgrade in the Hot-Dry and Mix-Dry climate zone has at least 5,000 sample houses (about 3%) in the 50+ years bin, which may be explained by homes without air conditioning or with very low heating setpoints. The window-only measures have longer, flatter distributions than the stand-alone insulation measure or the upgrade package measures, across all climate zones.

Net Present Value

Net present value (NPV) is a common metric for determining cost-effectiveness of energy efficiency measures from a homeowner's perspective. A positive NPV suggests that a measure would be a good investment for homeowners planning to own the home for the lifetime of the measure (or that the financing can be passed on to a future owner). The net present values are presented here as medians, alongside the standard deviation (sd), in Figure 12. Darker colors in the figure indicate median NPVs further from 0, with orange for negative median values and blue for positive median values. When organized in this way, by climate zone and vintage, all median NPVs are negative for stand-alone triple-pane windows. For the rest of the upgrades, all median NPVs are positive for the Cold & Very Cold and the Mixed-Humid climate zones, with lower positive values for the stand-alone low-E storm upgrade, the upgrade package that includes triple-pane windows, and newer vintages.

Figure 13 shows the percent of eligible homes in each climate zone and vintage range where the upgrade has a positive NPV.

Median NPV [2019$]

		Upgrade Name						
Building America Climate Zone	Vintage Range	1″ Insulation	Low-E Storms	Triple Pane	1″ Insulation & Low-E Storms	1″ Insulation & Triple Pane	2″ Insulation & Low-E Storms	1″ Insulation & Low-E Storms & Shading
Cold & Very Cold	Before 1950	4,146 (sd 7,180)	348 (sd 3,039)	-2,530 (sd 6,180)	4,106 (sd 8,380)	3,072 (sd 9,614)	4,390 (sd 9,560)	3,623 (sd 7,974)
	1950-1969	3,186 (sd 6,005)	257 (sd 2,569)	-2,282 (sd 5,300)	3,144 (sd 6,922)	2,404 (sd 7,975)	3,280 (sd 7,919)	2,804 (sd 6,653)
	1970-1989	710 (sd 3,534)	207 (sd 2,777)	-2,416 (sd 5,790)	681 (sd 4,463)	201 (sd 5,936)	434 (sd 5,039)	377 (sd 4,299)
Mixed-Humid	Before 1950	4,198 (sd 5,853)	204 (sd 2,359)	-2,843 (sd 5,313)	4,152 (sd 6,797)	2,899 (sd 7,977)	4,420 (sd 7,683)	3,662 (sd 6,474)
	1950-1969	3,694 (sd 4,897)	181 (sd 2,006)	-2,589 (sd 4,584)	3,678 (sd 5,685)	2,618 (sd 6,822)	3,856 (sd 6,419)	3,274 (sd 5,447)
	1970-1989	1,205 (sd 3,690)	102 (sd 1,971)	-3,020 (sd 4,717)	1,164 (sd 4,351)	186 (sd 5,921)	939 (sd 4,920)	749 (sd 4,269)
Marine	Before 1950	978 (sd 4,154)	-1,352 (sd 1,968)	-5,701 (sd 5,106)	270 (sd 4,980)	-781 (sd 7,097)	17 (sd 5,705)	-173 (sd 4,969)
	1950-1969	473 (sd 3,515)	-1,370 (sd 1,633)	-5,420 (sd 4,341)	-181 (sd 4,255)	-1,309 (sd 6,364)	-503 (sd 4,875)	-592 (sd 4,436)
	1970-1989	-668 (sd 2,832)	-1,413 (sd 1,714)	-5,709 (sd 4,726)	-1,208 (sd 3,611)	-2,177 (sd 6,232)	-1,729 (sd 4,145)	-1,657 (sd 4,144)
Hot-Dry & Mixed-Dry	Before 1950	41 (sd 3,761)	-1,357 (sd 1,785)	-5,819 (sd 4,750)	-795 (sd 4,669)	-2,561 (sd 6,916)	-1,228 (sd 5,358)	-883 (sd 4,808)
	1950-1969	283 (sd 3,743)	-1,120 (sd 1,597)	-5,335 (sd 4,363)	-466 (sd 4,537)	-2,381 (sd 6,590)	-870 (sd 5,210)	-591 (sd 4,638)
	1970-1989	-932 (sd 3,183)	-819 (sd 1,809)	-5,321 (sd 4,769)	-1,408 (sd 4,076)	-4,192 (sd 6,588)	-1,976 (sd 4,650)	-1,394 (sd 4,209)
Hot-Humid	Before 1950	1,470 (sd 3,076)	-523 (sd 1,521)	-4,465 (sd 4,577)	995 (sd 3,933)	-1,743 (sd 6,125)	819 (sd 4,419)	840 (sd 3,850)
	1950-1969	1,026 (sd 2,648)	-525 (sd 1,280)	-4,280 (sd 3,839)	576 (sd 3,384)	-2,192 (sd 5,327)	280 (sd 3,798)	447 (sd 3,281)
	1970-1989	-491 (sd 2,390)	-505 (sd 1,449)	-4,563 (sd 4,361)	-891 (sd 3,163)	-3,938 (sd 5,629)	-1,458 (sd 3,554)	-1,047 (sd 3,100)

Figure 12. Median and standard deviation of NPV for the seven upgrades, aggregated by climate zone and vintage range.

Building America Climate Zone	Vintage Range	1″ Insulation	Low-E Storms	Triple Pane	1″ Insulation & Low-E Storms	1″ Insulation & Triple Pane	2″ Insulation & Low-E Storms	1″ Insulation & Low-E Storms & Shading
		Upgrade Name						
Cold & Very Cold	Before 1950	96%	60%	26%	92%	77%	91%	87%
	1950-1969	95%	58%	25%	91%	76%	88%	86%
	1970-1989	65%	55%	26%	62%	54%	57%	57%
Mixed-Humid	Before 1950	99%	56%	20%	94%	75%	93%	90%
	1950-1969	98%	56%	20%	94%	75%	92%	90%
	1970-1989	72%	53%	17%	68%	52%	62%	62%
Marine	Before 1950	67%	16%	5%	54%	43%	50%	48%
	1950-1969	59%	12%	3%	48%	37%	44%	43%
	1970-1989	38%	12%	2%	31%	24%	28%	26%
Hot-Dry & Mixed-Dry	Before 1950	51%	12%	2%	38%	26%	35%	37%
	1950-1969	55%	14%	3%	43%	27%	40%	42%
	1970-1989	30%	23%	4%	27%	15%	24%	28%
Hot-Humid	Before 1950	81%	31%	5%	65%	37%	61%	63%
	1950-1969	74%	28%	4%	60%	32%	54%	57%
	1970-1989	39%	30%	5%	34%	17%	29%	32%

Figure 13. Percent of eligible homes in each climate zone and vintage range where the upgrade has a positive NPV.

Figure 14 shows how the simple payback periods are distributed in each climate zone. The upgrades that include triple-pane windows are much more negative than the other options. None of the distributions in the Marine, Hot-Dry & Mixed-Dry, or Hot-Humid climates center above 0. The spreads of the values are very wide for all upgrades other than low-E storm windows.

It is also interesting to look at the NPVs for the stand-alone upgrade options, organized by the baseline wall and window options, as shown in Figure 15 and Figure 16.

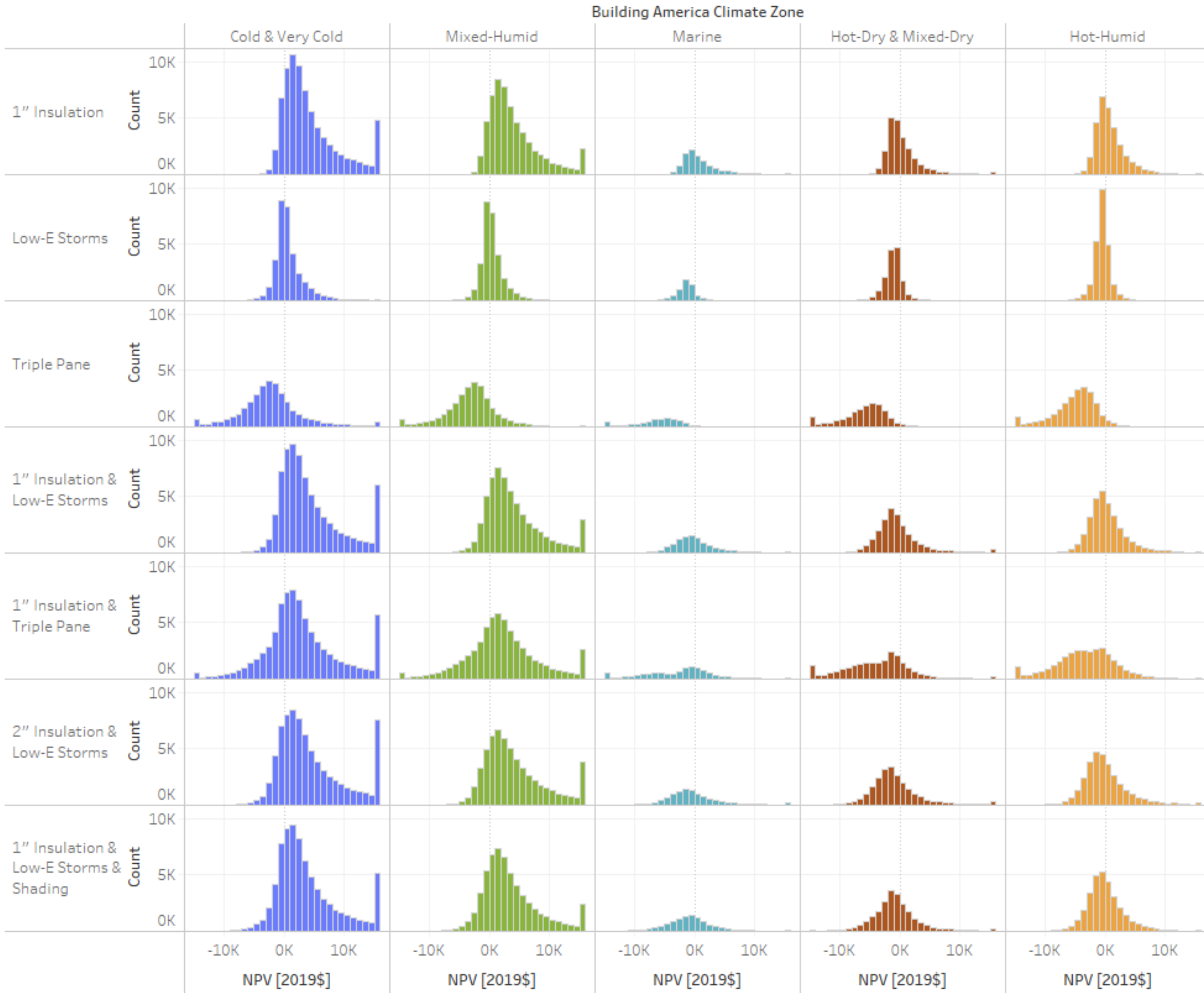

Figure 14. Distributions of NPV for all seven upgrades, separated by climate zone. The histograms use a bin size of $1,000, an overflow bin for $15,000 and higher, and an underflow bin for -$15,000 and lower.

Accounting for Increase in Home Resale Value

Siding and window upgrades typically increase the resale value of a home, recouping 67–68% of the job cost (national average), as documented in Remodeling Magazine's *Cost vs. Value Report*.[21]

Figure 16 shows that this has a significant impact on NPV calculations for window upgrades. The resale value would occur at some unknown time in the future when the home is sold; however, we did not discount the increase in resale value, so the alternate NPV should be considered a maximum value (i.e., if the home is sold immediately after the upgrade). For siding upgrades, our NPV calculations only include the upfront cost of insulation and not the siding itself, so there is not the same justification for accounting for the increase in home value (because the increase is assumed to come solely from the aesthetic improvement).

[21] https://www.remodeling.hw.net/cost-vs-value/2021/

Upgrade Name	Baseline Wall	Cold & Very Cold	Mixed-Humid	Marine	Hot-Dry & Mixed-Dry	Hot-Humid
		Building America Climate Zone				
1" Insulation	Wood Stud, Uninsulated	4,501 (sd 7,121)	4,017 (sd 5,314)	726 (sd 3,792)	345 (sd 3,951)	1,378 (sd 2,927)
	Wood Stud, R-7	798 (sd 3,271)	913 (sd 2,769)	-965 (sd 1,785)	-1,056 (sd 1,911)	-626 (sd 1,508)
	Wood Stud, R-11	420 (sd 3,131)	207 (sd 2,435)	-1,236 (sd 1,818)	-1,391 (sd 2,023)	-975 (sd 1,652)
	Wood Stud, R-15	320 (sd 2,958)				
	CMU, 6-in Hollow, Uninsulated	6,943 (sd 7,052)	2,865 (sd 3,849)	2,618 (sd 6,049)	554 (sd 2,639)	254 (sd 1,966)
	CMU, 6-in Hollow, R-7	3,204 (sd 3,459)	591 (sd 2,246)	-970 (sd 1,091)	-1,043 (sd 1,007)	-1,245 (sd 1,149)
	CMU, 6-in Hollow, R-11	1,887 (sd 3,242)	77 (sd 1,872)	-981 (sd)	-1,739 (sd 1,677)	-1,635 (sd 1,175)
	Brick, 12-in, 3-wythe, Uninsulated	2,634 (sd 4,369)	2,797 (sd 3,902)	57 (sd 2,758)	-574 (sd 2,195)	460 (sd 2,225)

Figure 15. Median and standard deviation of NPV for the 1" insulation upgrade, aggregated by climate zone and baseline wall type that the upgrade is applied to. The median NPV is positive in the two coldest climates, and is positive in other climates when applied to uninsulated wood stud or concrete masonry unit (CMU) walls.

Building America Climate Zone	Baseline Window	NPV (using full upfront cost): Low-E Storms	NPV (using full upfront cost): Triple Pane	NPV accounting for increased home value (using only 33% of upfront cost): Low-E Storms	NPV accounting for increased home value (using only 33% of upfront cost): Triple Pane
Cold & Very Cold	Single, Clear, Metal	345 (sd 2,776)	-1,629 (sd 6,295)	1,983 (sd 3,042)	2,993 (sd 6,440)
	Single, Clear, Non-metal	605 (sd 2,985)	-2,063 (sd 5,907)	2,290 (sd 3,278)	2,543 (sd 5,517)
	Double, Clear, Metal, Air	-119 (sd 2,236)	-3,389 (sd 4,616)	1,444 (sd 2,227)	1,062 (sd 3,446)
	Single, Clear, Metal, Exterior Clear Storm	-944 (sd 1,790)	-2,391 (sd 5,882)	429 (sd 1,450)	1,889 (sd 5,814)
	Single, Clear, Non-metal, Exterior Clear Storm	-898 (sd 1,741)	-3,115 (sd 5,583)	520 (sd 1,427)	1,235 (sd 4,519)
Mixed-Humid	Single, Clear, Metal	205 (sd 1,817)	-2,186 (sd 4,675)	1,923 (sd 2,028)	2,738 (sd 4,184)
	Single, Clear, Non-metal	512 (sd 2,274)	-2,392 (sd 5,020)	2,216 (sd 2,563)	2,426 (sd 4,274)
	Double, Clear, Metal, Air	-223 (sd 1,746)	-3,901 (sd 4,141)	1,457 (sd 1,739)	971 (sd 2,534)
	Single, Clear, Metal, Exterior Clear Storm	-1,186 (sd 1,587)	-3,177 (sd 5,050)	373 (sd 976)	1,666 (sd 3,653)
	Single, Clear, Non-metal, Exterior Clear Storm	-1,054 (sd 1,613)	-3,672 (sd 5,169)	487 (sd 1,124)	1,208 (sd 3,558)
Marine	Single, Clear, Metal	-1,412 (sd 1,598)	-5,438 (sd 4,576)	9 (sd 1,192)	-629 (sd 2,684)
	Single, Clear, Non-metal	-1,123 (sd 1,819)	-5,348 (sd 4,708)	443 (sd 1,779)	-494 (sd 3,037)
	Double, Clear, Metal, Air	-1,659 (sd 1,684)	-6,131 (sd 4,627)	-44 (sd 1,085)	-1,042 (sd 1,992)
	Single, Clear, Metal, Exterior Clear Storm	-1,875 (sd 1,996)	-5,390 (sd 6,116)	-319 (sd 751)	-823 (sd 2,327)
	Single, Clear, Non-metal, Exterior Clear Storm	-1,894 (sd 1,448)	-5,940 (sd 4,587)	-270 (sd 730)	-1,006 (sd 2,318)
Hot-Dry & Mixed-Dry	Single, Clear, Metal	-705 (sd 1,748)	-4,887 (sd 4,654)	887 (sd 1,712)	61 (sd 3,042)
	Single, Clear, Non-metal	-1,149 (sd 1,799)	-5,521 (sd 4,648)	397 (sd 1,670)	-709 (sd 2,765)
	Double, Clear, Metal, Air	-1,139 (sd 1,582)	-5,810 (sd 4,426)	479 (sd 1,334)	-684 (sd 2,192)
	Single, Clear, Metal, Exterior Clear Storm	-1,912 (sd 1,440)	-5,949 (sd 4,852)	-247 (sd 755)	-929 (sd 2,983)
	Single, Clear, Non-metal, Exterior Clear Storm	-1,898 (sd 1,351)	-6,225 (sd 4,414)	-296 (sd 652)	-1,327 (sd 2,045)
Hot-Humid	Single, Clear, Metal	-364 (sd 1,301)	-4,054 (sd 4,066)	1,308 (sd 1,413)	966 (sd 2,643)
	Single, Clear, Non-metal	-508 (sd 1,449)	-4,410 (sd 4,154)	1,106 (sd 1,471)	543 (sd 2,391)
	Double, Clear, Metal, Air	-687 (sd 1,343)	-5,154 (sd 4,304)	963 (sd 1,170)	-110 (sd 1,769)
	Single, Clear, Metal, Exterior Clear Storm	-1,609 (sd 1,492)	-5,102 (sd 4,805)	50 (sd 668)	114 (sd 2,474)
	Single, Clear, Non-metal, Exterior Clear Storm	-1,466 (sd 1,478)	-4,899 (sd 4,827)	96 (sd 632)	-85 (sd 2,031)

Median Net Present Value ($)
-5,000 5,000

Figure 16. Median and standard deviation of NPV for two window upgrades, aggregated by climate zone and baseline window type that the upgrade replaces. The NPV values are presented using both the standard calculation (using the full upfront cost) and with an alternate calculation that accounts for the fact that window upgrades typically recoup 67% of their cost at resale.

Source: https://www.remodeling.hw.net/cost-vs-value/2021/

4 Conclusions

The analysis presented in this document used ResStock simulations to produce distributions of site energy savings, bill savings, simple payback period, and NPV for seven different upgrade scenarios applied across the single-family detached housing stock in the contiguous United States. One conclusion from this work is that the cost-effectiveness of these upgrades can vary widely; the median NPV is sometimes positive and sometimes negative, but in most cases, the standard deviation of the distribution spans both negative and positive NPV values. This variation is due to diversity in housing stock characteristics and occupant behavior, climate variations within each climate zone, and electricity and fuel price differences between states. One limitation of this work is that we used single values (no variation based on location or other factors) for the cost of each upgrade per square foot of exterior wall or window. Including such variation may further increase the variability in NPV. Another caveat is that the NPV calculations are sensitive to the assumed 3.4% real discount rate and 30-year analysis period, and the NPV calculations did not include a residual value for insulation at the end of the 30-year analysis period.

With the variation in NPV in mind, there are several conclusions that can be made (all drawn from Figure 13 unless otherwise specified):

- In Cold and Mixed-Humid climate homes built before 1970, adding insulation at time of re-siding is almost always cost-effective—the NPV is positive for at least 95% of eligible homes (21.6 million).
- In homes built before 1970 in warmer climates, the NPV of adding insulation at time of re-siding is positive for a majority—at least 50%—of eligible homes (5.6 million).
- When 1” insulation at time of re-siding is bundled with low-E storm window upgrades, the packages are still cost-effective in at least 90% of eligible homes built before 1970 in Cold and Mixed-Humid climates (20.7 million).
- When 1” insulation at time of re-siding is bundled with triple-pane window upgrades, the packages are still cost-effective in at least 75% of eligible homes built before 1970 in Cold and Mixed-Humid climates (17 million).
- Window upgrades alone are less likely to be cost-effective, with a positive NPV in:
    - About 60% of eligible homes (8.6 million) in Cold and Mixed-Humid climates for low-E storms
    - About 20% of eligible homes (3.5 million) in Cold and Mixed-Humid climates for triple-pane windows.

Our analysis uniquely included an alternate NPV calculation for window replacements that accounted for the expected increase in home resale value:

- As shown in Figure 16, if one includes the increase in home resale value due to window replacement in the NPV calculation (undiscounted), then these values change dramatically, with a positive NPV in:
    - About 98% of eligible homes (15.2 million) in Cold and Mixed-Humid climates for low-E storms

   - About 86% of eligible homes (13.4 million) in Cold and Mixed-Humid climates for triple-pane windows
   - About 95% of eligible homes (5.5 million) in Hot-Humid climates for adding low-E storms to non-low-E single- or double-pane windows without storms
   - About 70% of eligible homes (3.1 million) in Hot-Humid climates for triple-pane windows replacing single-pane windows without storms.

We make several final conclusions by comparing the cost-effectiveness of different measures and packages:

- Across all climate zones, low-E storm windows save less energy per household than the other two stand-alone measures (1” insulation and triple-pane windows). 1” insulation has better cost-effectiveness than triple-pane windows, even when accounting for the increase in home resale value. This suggests that if one had to focus on pairing only one of the three measures with siding updates, then it would make sense to focus on 1” insulation, though there might be other reasons, such as thermal comfort, to promote window upgrades as well.
- Based on our upfront cost assumptions, there is little difference in the cost-effectiveness of 1” insulation and 2” insulation (both modeled with low-E storms). Increasing from 1” to 2” increases annual bill savings by \$50–\$100 (Figure 8), but practical challenges may make 2” insulation retrofits less desirable than 1” or 1.5”.
- Exterior shading does not appear to add a lot of value; including it in a package with 1” insulation and low-E storms has an equal or slightly lower chance of cost-effectiveness in all cases.

These conclusions can help inform retrofit recommendations and market transformation efforts in the re-siding and window replacement markets. Future work will seek to increase adoption in residential facade upgrades by partnering with existing programs to promote retrofits, expand the contractor base, and advance homeowner recruitment efforts.