Opening the Window to Space Heating Decarbonization for Communities

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Abstract

The transition to a sustainable and decarbonized energy system is imperative in mitigating climate change. A primary challenge in this endeavor is reducing the energy use and on-site carbon emissions from space heating. While heat pumps are considered a primary strategy to decarbonize HVAC and provide more efficient cooling, their affordability and efficiency are uncertain because of the equipment and possible panel upgrade cost associated with the heat pump and backup heating. Over 60% of U.S. residential windows remain low-performing clear glass. Given the heating energy savings potential of window upgrades, this study aims to quantify their role in advancing space heating decarbonization in residential communities.

This paper presents a multi-stage study. In the first stage, we investigate the impact of various window upgrades (code minimum, ENERGY STAR, highly-insulated, and low-E storm windows) on heat pump sizing and energy use at the building-level for cities and counties across the U.S. utilizing EnergyPlus simulation. The second stage extends the simulation using ResStock to assess how these strategies can scale to influence the entire U.S. building stock. We evaluate triple-pane window upgrades combined with heat pumps at both the national and electric grid independent system operator levels. The results show that window upgrades, when paired with high-efficiency heat pumps, can reduce backup heating and heat pump capacities, and yield significant energy and carbon savings. The greatest savings occur at summer and winter peak hours in most regions, indicating that window upgrades could enable more electrification within the limitations of the existing electricity system.

Introduction

Encouraging Space Heating Decarbonization - Importance and Challenges. In 2020, space heating maintained its position as the primary energy-consuming end use in U.S. homes, as revealed by the Energy Information Agency’s (EIA) Residential Energy Consumption Survey (RECS). Heating homes constituted 42% of site energy use within the residential sector (EIA 2023). This significant energy use is primarily served by fossil fuel-fired equipment and thus contributes to a substantial portion of buildings’ carbon emissions. Decarbonizing space heating is crucial for meeting climate goals and reducing the environmental footprint of buildings. Heat pumps, which efficiently transfer heat from one space to another, offer a promising solution for decarbonizing space heating by switching fuel uses to electricity.

A recent study (Waite and Modi 2020) modeled building space heating electrification across the U.S. Their modeling results revealed that transitioning to all-electric heating could potentially increase aggregated peak loads by 70%. This increase in load will impose significant costs to increase grid capacity. Even though highly efficient heat pumps are expected to mitigate load issues, choosing these heat pumps involves higher upfront costs, sizing complexities, and the need for backup heating during extreme weather conditions.

Why Window Upgrades Are an Appealing Accompanying Retrofit. The effectiveness of heat pumps can be compromised by inefficient building envelopes, particularly poorly performing windows, which are typically the largest cause of heat loss and increased energy use from the building envelope. Upgraded windows enhance the overall energy efficiency and comfort of buildings. This, in turn, can increase resilience and reduce overall and peak heating and cooling demands, thereby optimizing the benefits of heat pump systems.

At the individual building level, window upgrades enhance thermal comfort, reduce energy costs, and mitigate the need for backup heating. In the broader community context, the adoption of window upgrades alongside heat pump installations can lead to collective energy savings, reduce pressure on local utility infrastructure and enhance community resilience. Furthermore, at the grid level, decreased energy demand resulting from efficient building practices, including window upgrades and efficient heat pumps, contributes to grid stability and resilience, particularly during peak demand periods and extreme weather conditions.

The current market share of ENERGY STAR™ Version 6 for new and retrofit window installations is about 86% across the country (FGIA 2023) but, based on reports from Ducker Research on the U.S. market for windows, doors, and skylights, coupled with recent data from RECS, clear glass windows remain the predominant glazing type, comprising over 60% of U.S. homes. This means that there remains significant market potential for high performance windows, indicating an opportunity for increased application of window upgrades accompanying other building decarbonization retrofits.

Objectives. This study aims to identify the impact of window upgrades on multiple dimensions of residential space heating decarbonization across the nation. Specifically, it focuses on heat pump sizing and backup heating requirements, associated panel upgrades, resulting energy usage and utility expenses, as well as grid-level dynamics, and their implications for building decarbonization and resilience. The specific objectives are:

- Identify the impact of window upgrades on the sizing of the heat pump and required backup heating nationwide, considering regional variations.
- Quantify the energy use and utility cost reduction achievable through window upgrades coupled with heat pump installations.
- Evaluate the impact of window upgrades and heat pump adoption on winter and summer peak demands at the grid level, informing considerations for grid stability and capacity planning.
- Assess the implications of window upgrades and heat pump integration on CO2 emissions reductions, contributing to broader decarbonization goals.

Methodology

A two-stage analysis is conducted to analyze the impact of window upgrades and heat pump integration for both individual buildings and the building stock. The first stage aims to identify the impact on a prototype house located in representative cities, and expanded to all counties to provide an initial national impact assessment. At this stage, six window performance levels are examined. The goal of the second stage is to scale up the simulation and analysis to the national building stock level, allowing for insights at the grid level. Informed by the findings from the single building analysis, this stage narrows down the window performance levels and leverages a statistically-representative characterization of the residential building stock for the assessment.

Methodology of the Single Building Analysis

From Representative Cities to All Counties. Prototype single-family houses for 132 representative cities (Taylor, Mendon, and Fernandez 2015) are simulated using EnergyPlus™ to obtain an overview of the national impacts, and regional variations, of combined window upgrades and heat pump installation. The prototype model with the predominant foundation type in each location, determined by RECS 2015, is selected. The key simulation inputs and outputs are utilized to train a 2-layer convolutional neural network (CNN) model. Subsequently, this CNN model extrapolates the results to all counties, incorporating climate (heating degree days) and location-related (lat, long, wall U-value, roof U-value, window U-value, and SHGC) parameters specific to each county, estimating the backup heating and annual energy use. Note that because the simulated heat pump models differ by region, it is difficult to fit a CNN model for heat pump characteristics. Thus, heat pump sizing results are not expanded to counties.

Window and Heat Pump Modeling Assumptions. At this single building analysis stage, one baseline window and six window upgrade options are examined. For IECC climate zones 1–4, the baseline window is considered to be single clear glazing with an aluminum frame. For the remaining climate zones, a double clear window with a wood frame is assumed to be the baseline window for prototype houses. For each location, window upgrade options include 1) code-minimum window, where the U-value and Solar Heat Gain Coefficient (SHGC) are based on the most recent local codes as of November 2022 (retrieved from UpCodes[1] platform); 2) ENERGY STAR Version 6 window, where the U-value and SHGC meet the recommendations for corresponding ENERGY STAR climate zone; 3) ENERGY STAR Version 7 window; 4) ENERGY STAR Most Efficient window; 5) highly-insulating window representing current maximum technology level; 6) low-E storm window, where the U-values and SHGC are obtained from the AERC certified product list. Window upgrades also reduce building air leakage, which is considered in all upgrade options, where the assumed infiltration rate through windows is decreased from 2 cfm/ft^2 to 0.3 cfm/ft^2.

Table 1. List of Window Upgrade Options

	U	SHGC
Code Minimum	Location dependent (Retrieved from UpCodes)	Location dependent (Retrieved from UpCodes)
ENERGY STAR V6	Northern: 0.27 North-central: 0.3 South-central: 0.3 Southern: 0.4	Northern: 0.27 North-central: 0.27 South-central: 0.25 Southern: 0.25

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[1] https://up.codes/codes/general

ENERGY STAR V7	Northern: 0.22 North-central: 0.25 South-central: 0.28 Southern: 0.32	Northern:0.26 North-central: 0.28 South-central: 0.22 Southern: 0.23
ENERGY STAR Most Efficient	0.2	Use E* V7 values
Highly-insulating Window (R10)	0.01	Use E* V7 values
Low-E Storm	0.27	0.45 for ENERGY STAR northern & north-central regions; 0.3 for ENERGY STAR southern & southern-central regions.

The primary focus of this analysis is to ascertain whether upgrading windows could assist in the decision-making process of switching to heat pumps in existing homes or the selection of heat pumps for new homes. With that in mind, the baseline scenario assumes that a building starts with a heat pump in place. The objective is to determine whether window upgrades have the potential to reduce the required size of the heat pump and mitigate the necessity for backup heating. Heating electrification is not included in this modeling.

For climate zones 1–4, simulations are conducted using a single-speed heat pump model. For climate zones 5–8, a cold climate heat pump model is utilized. In this approach, a variable-speed heat pump is initially autosized. Note that EnergyPlus's heat pump model is autosized to meet the cooling load, which is not practical for all climates in the US. Thus, in this study, the heat pump is oversized by a factor of 1.5 to ensure sufficient heating capacity for cold climates. Later in the building stock analysis using Restock with more computation resources, another cooling-load-based sizing method - ACCA manual S sizing, and largest-design-load-based sizing method - Max load sizing, are further tested.

Methodology of the Building Stock Analysis

ResStock Tool Overview. For analyzing the decarbonization effects of window upgrades in the existing building stock, this study utilizes the ResStock™ analysis tool. ResStock™ is a building stock energy modeling tool with two primary functions: generating a set of residential dwelling models that are statistically representative of the United States' building stock and pairing those models with physics-based energy modeling software to calculate each respective dwelling's energy use.

Similar to the single building analysis, the physics-based modeling in ResStock is performed using EnergyPlus™ and OpenStudio™. Data sources that inform ResStock's sampling of statistically representative dwellings include the EIA RECS and Census-derived data like the American Community Survey Public Use Microdata Sample (Census Bureau 2024) and the American Housing Survey (Census Bureau 2021). Specific data sources for sampled dwelling and household characteristics can be found at the bottom of the housing characteristics files located in the publicly available ResStock repository[2].

National Analysis with Heat Pump and Window Upgrades. For this study, five upgrades as well as a baseline run were used to model the pairing of high efficiency heat pumps (HP) and high performance windows. Table 2 outlines the six scenarios. The window and heat pump upgrades (Scenarios 1–5) were only applied to dwellings built before 1990. This filter narrows the population of homes modeled to those that are most likely to have low-performing windows. The Baseline scenario (Scenario 0) includes all dwellings in the U.S., but its results are filtered to only dwellings built before 1990 in the results section for better comparison.

A Note on Heat Pump Sizing. Sizing of heat pumps is important because heat pump sizing increases are typically correlated with heat pump cost increases. ResStock has two primary options for sizing heat pumps—ACCA Manual J (ACCA 2016)/Manual S (ACCA 2014) or "Max Load." ACCA Manual J/S sizes the heat pump to the dwelling's cooling load with up to 1.5 tons of refrigeration in oversizing allowance for dwellings in cold, dry climates. Max Load sizing entails the heat pump being sized to whichever seasonal load is larger. Max Load sizing is not utilized in all climate zones because large units in cold climates can cause cooling season humidity issues and large units significantly increase the cost of the installation. Variable-speed heat pumps (like the ones modeled in this portion of the study) can mitigate these issues due to their variable output compressors. All heat pump upgrades in this building stock analysis include electric resistance backup systems. The backup system will provide the requisite amount of heat to fully cover the dwelling unit's heating load when the heat pump compressor cannot meet the load itself.

Table 2. A total of six scenarios were run in ResStock to calculate the performance of heat pump and window upgrades in the existing U.S. building stock

Scenario Number	Scenario Name	Heat Pump Specifications	Window Specifications
0	Baseline	Existing housing stock's HVAC saturation and specifications[3]	Existing housing stock's window saturation and specifications[4]
1	ACCA HP only	Variable speed air-source heat pumps - Ducted: SEER 24, HSPF 13 - Non-ducted: SEER 29.3, HSPF 14 - Sized to ACCA Manual J/S	Same as Baseline scenario
2	Triple pane* only	Same as Baseline scenario	Triple pane, Low-E, Insulated with Argon - IECC climate zones 1-3: L-Gain (U = 0.18, SHGC = 0.27)

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[2] https://github.com/NREL/resstock/tree/windows-heat-pump/project_national/housing_characteristics

[3] Based on EIA's RECS 2009 dataset: https://github.com/NREL/resstock/blob/windows-heat-pump/project_national/housing_characteristics/HVAC%20Heating%20Efficiency.tsv

[4] Based on EIA's RECS 2015 dataset: https://github.com/NREL/resstock/blob/windows-heat-pump/project_national/housing_characteristics/Windows.tsv

			- IECC climate zones 4-7: H-Gain (U 0.17, SHGC 0.4)
3	ACCA HP + triple pane*	Variable speed air-source heat pumps - Ducted: SEER 24, HSPF 13 - Non-ducted: SEER 29.3, HSPF 14 - Sized to ACCA Manual J/S	Triple pane, Low-E, Insulated with Argon - IECC climate zones 1-3: L-Gain (U = 0.18, SHGC = 0.27) - IECC climate zones 4-7: H-Gain (U = 0.17, SHGC = 0.4)
4	Max HP only	Variable speed air-source heat pumps - Ducted: SEER 24, HSPF 13 - Non-ducted: SEER 29.3, HSPF 14 - Sized to Max Load	Same as Baseline
5	Max HP + triple pane*	Variable speed air-source heat pumps - Ducted: SEER 24, HSPF 13 - Non-ducted: SEER 29.3, HSPF 14 - Sized to Max Load	Triple pane, Low-E, Insulated with Argon - IECC climate zones 1-3: L-Gain (U = 0.18, SHGC = 0.27) - IECC climate zones 4-7: H-Gain (U = 0.17, SHGC = 0.4)

* Triple pane windows upgrade includes whole-home infiltration reduction of 15% for upgrades from double pane windows and 30% for upgrades from single pane windows.

Table 3. Heat pump upgrade and window upgrade details with corresponding scenario numbers.

Scenarios	Heat Pump Upgrade	No	Yes	Yes
	Heat Pump Sizing	-	ACCA	Max Load
Window Upgrade	No	Scenario 0 “Baseline”	Scenario 1 “ACCA HP Only”	Scenario 4 “Max Size HP”
	Yes	Scenario 2 “Triple Pane Only”	Scenario 3 “ACCA + Triple Pane”	Scenario 5 “Max + Triple Pane”

Results and Discussion

Single Building Results

Example cities representative of different climate zones, shown in Table 3, are selected to showcase the main metrics relevant to the dimensions of interest: the size of the heat pump, the backup heating and associated service upgrades needed, annual electricity usage, and its implications on utility bills. The utility bill saving numbers are calculated using the local electricity rates as of 2021.

For these example cities, replacing the baseline window reduces the heat pump size by approximately 0.6–2.2 tons. The amount of backup heating required is similarly reduced, ranging from 0.4–6.7 kW. The most substantial reductions are observed in colder climates when the baseline windows are replaced with highly-insulating windows.

Table 3. Results for prototype houses in example cities

Location	Climate Zone	Windows	HP Size	Backup Heating Required (Breaker size)	Annual Energy Savings (kWh)	Annual Utility Bill Savings
Jackson, WY	7	Double clear, wood frame	4.3 ton	13,670 W (70 A)	NA	NA
		Code minimum	3.7 ton	12,280 W (70 A)	2,590	$282
		ENERGY STAR v6	2.8 ton	10,210W (60 A)	3,050	$333
		ENERGY STAR v7	2.5 ton	9,970 W (50 A)	3,420	$373
		ENERGY STAR most efficient	2.5 ton	8,890 W (50 A)	3,510	$383
		Highly-insulating (R10)	2.1 ton	6,950 W (40 A)	4,390	$479
		Low-E storm	2.8 ton	9,910 W (50 A)	3,010	$328
Phoenix, AZ	2B	Single clear, aluminum frame	4.7 ton	5,410 W (30 A)	NA	NA
		Code minimum	3.9 ton	5,040 W (30 A)	1,040	$150
		ENERGY STAR v6	3.5 ton	4,920 W (30 A)	1,250	$180
		ENERGY STAR v7	3.2 ton	4,155 W (20 A)	1,620	$233
		ENERGY STAR most efficient	3.0 ton	3,980W (20 A)	1,880	$271
		Highly-insulating (R10)	2.6 ton	3,440 W(20 A)	2,010	$290
		Low-E storm	3.3 ton	3,740 W (20 A)	1,190	$171

For all the representative cities, the heat pump capacities are reduced. Figure 1 shows an example of upgrading the windows to ENERGY STAR v7. By looking at the number of cities distributed in the plot, the heat pump sizes in most cities are reduced by 1.5 tons.

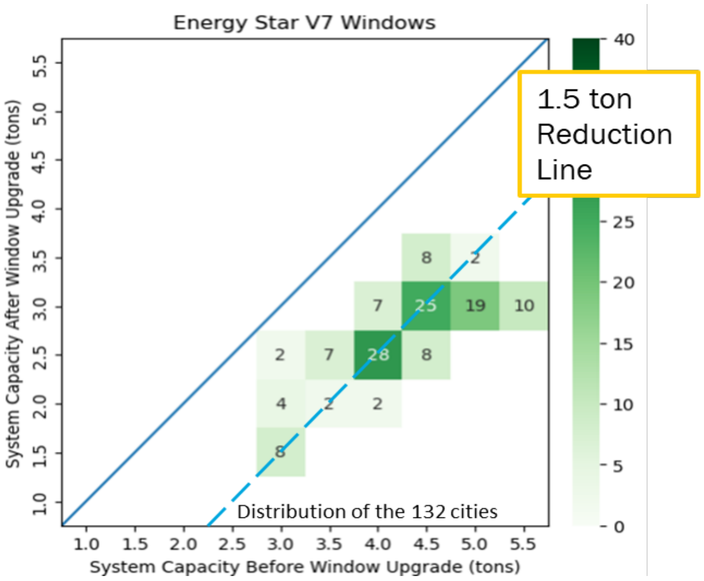

Figure 1. Heat pump size reduced by replacing baseline window with ENERGY STAR v7 window for the prototype house in 132 representative cities.

Expanding the results to all counties across the nation, a full picture of the range and variations of backup heating requirements and annual energy use is created. The maps in Figure 2 illustrate the magnitude of backup heating reduction and residual backup heating needed after replacing the baseline window with the ENERGY STAR v7 window. The warmer color in the upper portion of the map indicates that the backup heating is significantly reduced in climate zones 5–8. The peak demand for backup heating occurs during the coldest days when the heat pump cannot adequately meet the heating requirements. Thus, the greatest amount of backup heating needed aligns with colder regions that have the greatest heating loads, which results in a larger reduction potential in these regions. This is more evident when the results are aggregated by climate zones (Table 4). The backup heating is reduced by up to 4.8 kW, corresponding to a potential decrease in required panel size by 30 A. The remaining backup heating stays below 80 A across the country.

Table 4 summarizes the remaining backup heating needed after window retrofits by climate zones for all upgrade scenarios. The windows have significant impacts on the backup heating needed and its associated panel size. The largest improvement can be observed from highly-insulating windows, the breaker size stays below 50 A.

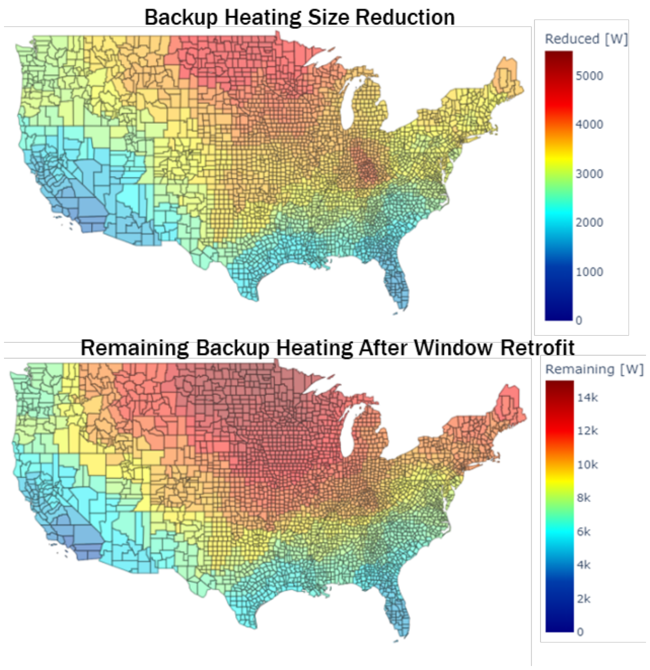

Figure 2. Backup heating size reduced by replacing the baseline window with ENERGY STAR v7 window for each county (top); remaining backup heating needed after window replacement (bottom).

Table 4. Remaining backup heating needed by climate zone

Climate Zone	Code Minimum		ENERGY STAR v6		ENERGY STAR v7		ENERGY STAR Most Efficient		Highly-insulating (R10)		Low-E Storm	
	Backup Heating Size (W)	Breaker Capacity (A)	Backup Heating Size (W)	Breaker Capacity (A)	Backup Heating Size (W)	Breaker Capacity (A)	Backup Heating Size (W)	Breaker Capacity (A)	Backup Heating Size (W)	Breaker Capacity (A)	Backup Heating Size (W)	Breaker Capacity (A)
5–7	10400–18500	60–100	8300–16,900	50–90	7200–14900	40–80	6900–12200	40–70	4550–8100	25–50	6900–12800	40–70
3–4	5900–13600	30–70	4100–12,700	20–70	3200–11,00	20–60	3100–10300	20–60	2800–6990	20–40	3100–10,200	20–60
1–2	4900–8100	25–40	4650–7800	25–40	4500–7500	25–40	4400–7400	25–40	3880–5500	25–30	4200–7300	25–40

Table 5 summarizes the annual energy use and utility cost savings for all window upgrade options. The most significant savings are observed in climate zones 5-7. Converting the energy saving numbers into utility bills, accounting for local electricity rates, households can anticipate a decrease in their bills ranging from $75 to $850 per year. The variations of results among ENERGY STAR v7, ENERGY STAR most efficient, and low-E storm windows are minimal.

Table 5. Annual energy savings and utility bill savings by climate zone

Climate Zone	Code minimum		ENERGYSTAR v6		ENERGYSTAR v7		ENERGYSTAR Most Efficient		Highly-insulating (R10)		Low-E Storm	
	Energy Saving (kWh)	Utility Cost Saving	Energy Saving (kWh)	Utility Cost Saving	Energy Saving (kWh)	Utility Cost Saving	Energy Saving (kWh)	Utility Cost Saving	Energy Saving (kWh)	Utility Cost Saving	Energy Saving (kWh)	Utility Cost Saving
5–7	950–3120	$105–$340	1300–4270	$160–$470	1,750–5020	$160–$550	1990–5960	$220–$655	4950–7750	$550–$850	2110–5590	$230–$620
3–4	910–1780	$105–$195	1120–2620	$130–$290	1400–3780	$160–$410	1960–4410	$220–$490	3990–5550	$450–$600	1210–2980	$140–$330
1–2	720–1030	$75–$115	960–1280	$115–$140	1380–1730	$150–$180	1,590–2,210	$180–$245	2590–4110	$285–$450	1220–1800	$135–$210

Building Stock Results

Results shown in this section incorporate all dwelling models built before 1990. This subset of dwellings is highlighted because of its high saturation of low-performing windows.

Dwelling Models by Climate Zone and ISO. Table 6 and Table 7 show the number of dwellings in these results by 2004 IECC Climate Zone and ISO/RTO (Independent System Operator/Regional Transmission Organization) respectively.

Table 6. Dwelling model count by ISO/RTO region. Note: only dwelling models with a vintage before the 1990s are shown.

ISO/RTO Region	Sample Count	Percent of Total Housing Stock
CAISO	23,089	4.2%
ERCOT	18,432	3.4%
MISO	42,419	7.7%
NEISO	12,646	2.3%
NYISO	15,135	2.8%
PJM	53,240	9.7%

SPP	13,073	2.4%
None	95,438	17.4%
Total	273,472	49.7%

Table 7. Dwelling model count by 2004 IECC Climate Zone. Note: only dwelling models with a vintage before the 1990s are shown.

2004 IECC Climate Zone	Sample Count	Percent of Total Housing Stock
1A	4,956	0.9%
2A	32,031	5.8%
2B	5,154	0.9%
3A	36,473	6.6%
3B	29,710	5.4%
3C	7,677	1.4%
4A	57,375	10.4%
4B	2,430	0.4%
4C	7,488	1.4%
5A	60,169	10.9%
5B	9,859	1.8%
6A	15,534	2.8%
6B	2,376	0.4%
7A	1,955	0.4%
7B	285	0.05%
Total	273,472	49.7%

These tables can be used to determine whether a cross-section of this study's building stock results meets the reliability threshold of 1,000 samples as discussed in NREL's EULP methodology report (Wilson et al. 2022). For example, the only subset of dwellings that may not provide reliable results is 2004 IECC Climate Zone 7B. For more information on sample sizes and ResStock, see Section 4 of the ResStock Dataset 2024.1 Documentation (Present et al. 2024).

Nationwide Results – Summer Peak and Winter Peak Days. Figures 3 show the respective 2018 peak winter and peak summer days nationwide for all dwellings built before 1990 across all six scenarios. It shows the peak reduction effects of triple pane windows across all scenarios. For ACCA HP and Max Load HP scenarios, the addition of triple pane windows decreases the peak significantly; notably, the peak is reduced by ~50 GW (~12.5%) for the ACCA sized HP scenario due to the addition of triple pane windows. The max load HP + triple pane scenario's load shape is lower than baseline at all hours except for the morning peak, where its averaged demand is only 3.5% higher than baseline; in effect, the addition of triple pane windows to a full electrification scenario creates a scenario with very similar load shapes to that of baseline.

For the summer peak, more efficient heat pumps reduce the peak demand by ~25 GW (~14%) while combining them with triple pane windows yields an additional peak demand reduction of ~10 GW (~6%). Across all upgrade scenarios, electricity demand is reduced compared to the baseline.

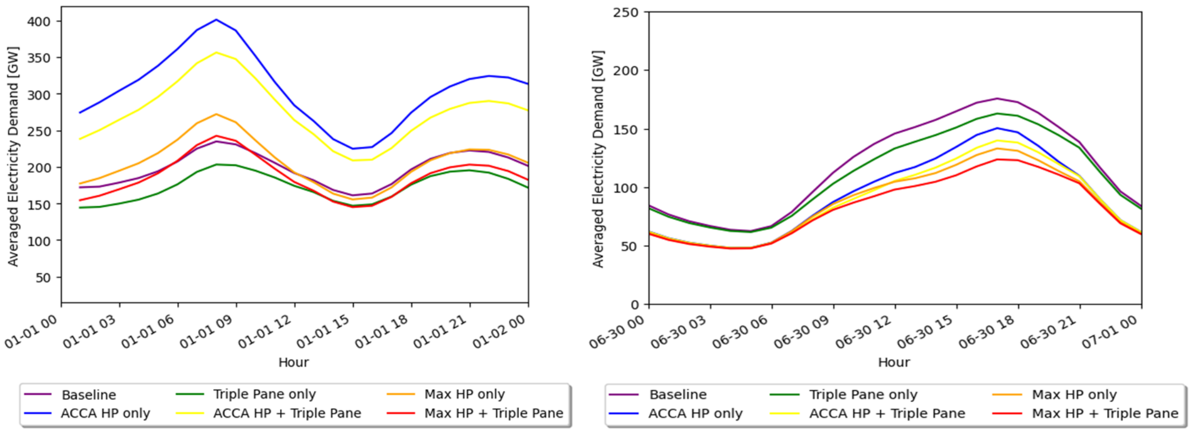

Figure 3. Nationwide winter and summer peak day across all scenarios. X-axis ticks are in MM-DD-HH format. (Left: winter peak; Right: summer peak.)

Results by Electric Grid Independent System Operator (ISO). Because of the regionality of weather, some areas see more intense local effects from cold and/or hot temperatures on their respective summer and winter peak days. Additionally, due to the effects of heat pump sizing methods and the new electricity demand from heating electrification, these results are segmented by ISO.

Figure 4 shows the 2018 winter peak for the New York Independent System Operator (NYISO)—a heating-dominated region—for the ACCA HP only and ACCA + Triple Pane scenarios. For results from a summer peaking grid system, Figure 5 shows the 2018 summer peak in the Electricity Reliability Council of Texas (ERCOT) region with the same two scenarios as NYISO. Figure 4 also includes the contribution of compressor heating and electric back-up heating to the total provided by the ACCA sized heat pump system. Compressor heating corresponds to the time-averaged electricity demand for heating the indoor space delivered by the heat pump refrigeration cycle. The electric backup heating is the requisite additional electric resistance heating provided by the backup system to meet the full heating load of the dwellings. Backup heating is less efficient than the heat pump refrigeration cycle but is heavily utilized by ACCA-sized heat pumps in heating-dominated climates.

The addition of triple pane windows, as shown in Figure 4, reduces the peak demand by ~5 GW (~14%). The majority of these 5 GW come from the reduction in required backup electric resistance heating. This reduction of backup heating means that the addition of high performance windows increases a dwelling's percent utilization of the higher efficiency compressor, rather than the lower efficiency electric resistance backup heating coil.

Figure 5, showing the peak summer day in the ERCOT region, portrays a similar takeaway. The triple pane windows reduce the summer peak by ~1.5 GW (~11%). This reduction eases the challenge of balancing the independent Texas grid during the hottest days of the year.

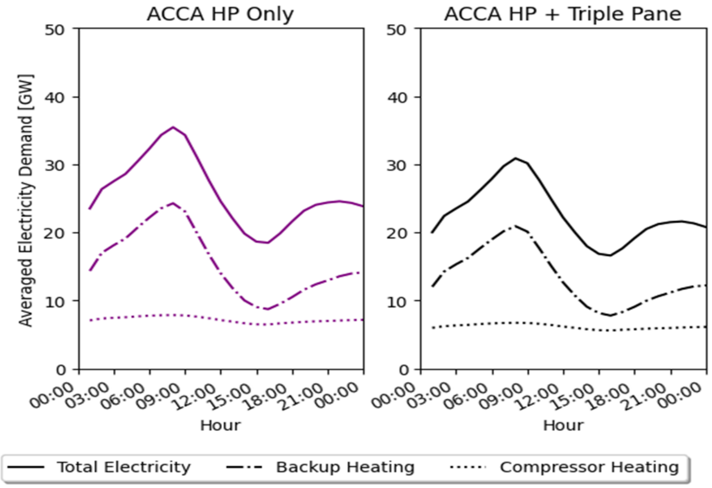

Figure 4. Average electricity demand in NYISO on the peak winter day.

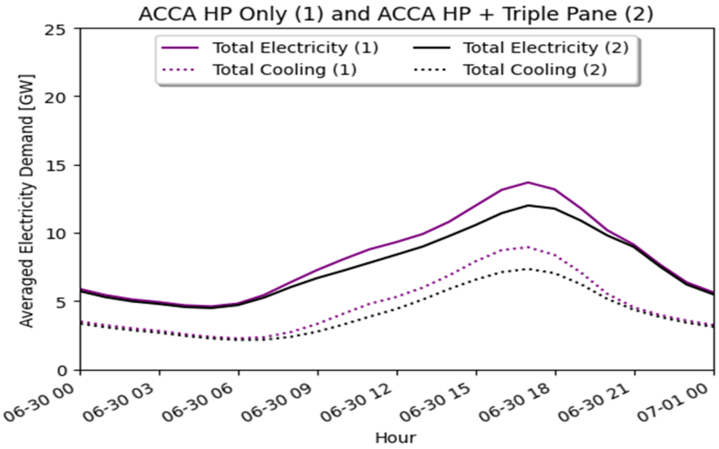

Figure 5. Average electricity demand in ERCOT on the peak summer day.

Emissions Factor Selection and Savings. These reductions in demand during all times of the year, but especially during peak days, translate into savings in CO2 equivalent (CO2e) emissions. Emissions factors were taken from NREL's Cambium dataset5. Specifically, the Cambium 2021 Mid-Case Long Run Marginal Emissions Rate (LRMER) data were used for this study. The LRMER describes the change in emissions from a change in electric load—it considers how a change in electric load could influence the structure of the electric grid. The Mid-Case Cambium scenario projects mid-level (i.e., business-as-usual) assumptions for demand growth, resource, system cost, fuel price, and technology inputs to estimate the emissions factors.

Figure 6 shows the emissions savings in CO2e for all upgrade scenarios using the Cambium 2021 Mid-Case LRMER data for a 2025 start. The majority of emissions savings in the electrification scenarios are due to electrification (i.e., displacing fossil fuel point sources in households) and higher efficiency cooling compared to the baseline. The addition of triple-pane windows increases savings for each of the base electrification scenarios.

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[5] https://www.nrel.gov/analysis/cambium.html

Impacts of High Performance Windows on Heat Pump Backup Sizing. A positive knock-on effect from the addition of high performance windows to dwellings with heat pumps is the reduction in heat pump back-up sizing. A reduction in heat pump backup size reduces the equipment cost to the consumer and reduces the potential need for electric panel upgrades because of a heat pump installation.

Figure 7 shows a boxplot of the backup heating coil size for all scenarios. Note that in the current residential stock, the large majority of dwellings do not have heat pumps, which is why the Baseline and Triple Pane Only scenarios have nearly nonexistent boxplots. These results show that triple pane windows reduce back-up heating size by 15% for both heat pump sizing scenarios. This reduction likely means that the consumers would see a cost reduction in avoided panel upgrades (due to the 15% decrease in backup size) and heat pump equipment cost (due to a smaller size heat pump) because of the improved envelope of the house.

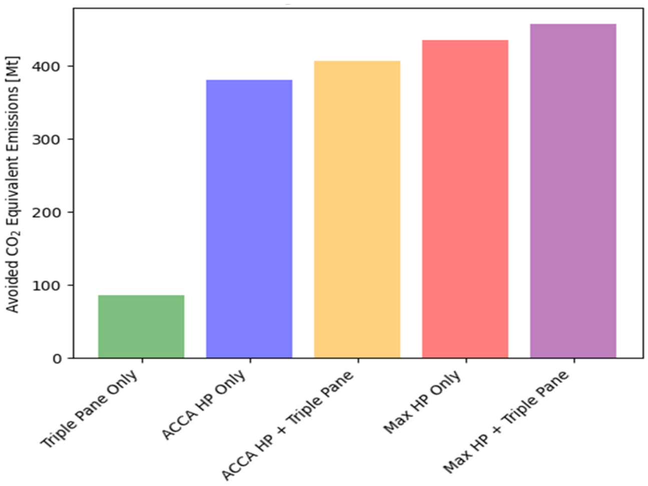

Figure 6. Emissions savings in CO2e for all upgrade scenarios. Higher savings are obtained in the scenarios that include 100% electrification of space heating.

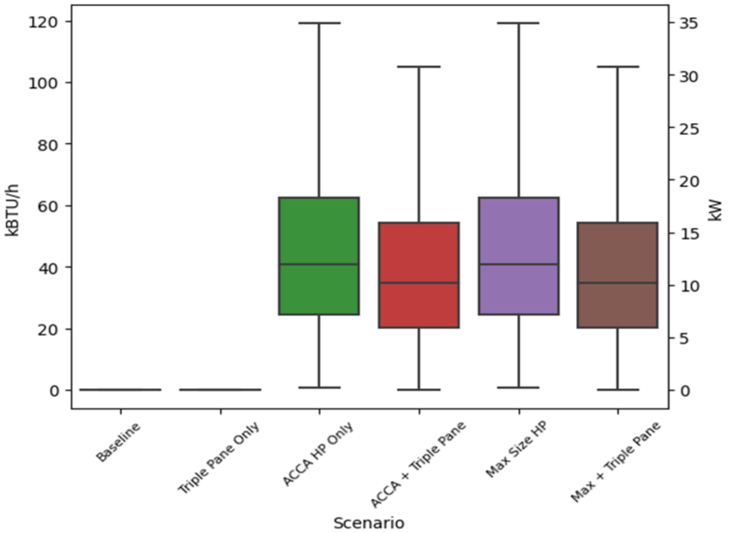

Figure 7. Backup heating size for all upgrade scenarios.

Conclusion

This study sheds light on the critical potential contribution of window upgrades in enhancing space heating decarbonization, specifically heat pump installation, at both the individual building level and across the U.S.

For prototype single-family houses, by examining high-performance windows including code-compliant windows, ENERGY STAR windows, highly-insulating windows, and low-E storm windows, the findings reveal that these window upgrades result in a notable reduction in heat pump size, averaging between 1 to 2 tons. This downsizing will contribute to reduced upfront costs for homeowners. For all regions, particularly in cold climates where large amounts of backup heating are needed in extreme weather conditions, window upgrades minimize the need for backup heating. This reduction can lead to a significant decrease in circuit size, up to 80 A. Window upgrades and heat pump integration reduce the energy usage and electricity bills for each household, which likely shortens the payback cycle of retrofits. The most savings are observed in regions where the high cost of electricity relative to low gas prices poses challenges to the economic viability of heat pump installations (e.g., Midwest). The confidence in promoting electrification is bolstered if window upgrades are pursued alongside in such regions.

The building stock analysis further supports the idea that combining window upgrades with heat pump installation can effectively reduce the size of the heat pump and backup heating needed. The results for heating-dominant NYISO and cooling-dominant ERCOT underscore the substantial impact of window upgrades on peak demand during both winter and summer peak days. The addition of triple pane windows results in significant reductions in peak demand. Notably, for the ACCA sized heat pump scenario, the incorporation of triple pane windows led to a ~50 GW reduction in winter peak demand, highlighting the potential for window upgrades to enhance grid resilience. Moreover, these reductions lead to considerable reduction in carbon emissions, with the majority of the savings attributed to electrification and more efficient cooling because of heat pump installation. The addition of triple pane windows increases the savings further.

This study explores different heat pump sizing methods. Sizing is crucial for efficiency, equipment cost, operation cost, and comfort. The results of this study also imply that sizing affects these benefits when integrated with other energy efficiency measures. Max load sized heat pumps show larger savings in peak demands than ACCA sized heat pumps. Future work should gather field data on equipment sizing and real-world performance to inform modeled interactions between building envelope performance and heat pump sizing.

Moving forward, it is imperative for policymakers, industry stakeholders, and homeowners to prioritize investments in high-performance windows to accelerate the transition to electrified and decarbonized buildings.

Acknowledgement

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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