Impact of Building Envelope Thermal Insulation on Use-Phase Emissions – Final Report

Submitted to:
Insulation Industry

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Executive Summary

ICF carried out an energy and carbon modelling study to analyze the potential use-phase emission reductions realized through the installation of building envelope insulation for residential and commercial new construction. The study focused on one residential prototype: single-family detached home, and six commercial prototypes: midrise apartment building, medium office, retail strip mall, primary school, secondary school, and warehouse.

The present study utilized the prototypical energy models developed by Pacific Northwest National Laboratory (PNNL) for code-compliant buildings in 16 climate zones: CZ1A, CZ2A, CZ2B, CZ3A, CZ3B, CZ3C, CZ4A, CZ4B, CZ4C, CZ5A, CZ5B, CZ5C, CZ6A, CZ6B, CZ7, CZ8. The models were adapted and simulated to explore the energy and carbon impact of insulation materials in the building envelope. For the residential prototype, the impact of insulation in exterior wall, attic floor and foundation walls was analyzed. For the commercial prototypes, the impact of insulation in exterior wall, roof and slab perimeter was analyzed. The range of lifetime carbon emissions per functional unit of insulation materials were reported for the different climate zones.

A total of 256 models (4x4x16) were simulated for the residential prototype, spanning four different foundation types, four different heating systems, and 16 climate zones. The foundation types are: vented crawlspace, heated basement, slab-on-grade, unheated basement. The heating systems are: electric resistance, natural gas furnace, fuel oil furnace and electric air-source heat pump. For the commercial prototypes, a total of 96 models (6x16) were simulated, spanning six building types: midrise apartment building, medium office, retail strip mall, primary school, secondary school and warehouse prototypes, and 16 different climate zones. Typical meteorological year (i.e., TMY3) weather data was obtained for cities representative of the 16 climate zones.

This study investigated the following scenarios:

1. Residential Prototype – Single-family Detached Home
   - R0 – No Insulation: this scenario models the home exterior envelope with no insulation.
   - R1 – Exterior Wall Insulation: this scenario models the home with only exterior wall insulation.
   - R2 – Foundation Insulation: this scenario models the home with only foundation insulation.
   - R3 – Attic Floor Insulation: this scenario models the home with only attic floor insulation.
   - R4 – Fully Insulated Home: this scenario models a home with an entirely insulated envelope.
2. Commercial Prototypes – Midrise Apartment Building, Medium Office, Retail Strip Mall, Primary School, Secondary School, and Warehouse
   - C0 – No Insulation: this scenario models the building envelope with no insulation.
   - C1 – Exterior Wall Insulation: this scenario models the building with only exterior wall insulation.
   - C2 – Slab Perimeter Insulation: this scenario models the building with only slab perimeter insulation.
   - C3 – Roof Insulation: this scenario models the building with only roof insulation.

- C4 – Fully Insulated Building: this scenario models the building with an entirely insulated envelope.

The minimum insulation R-values required by code (IECC 2021 for the residential prototype and ASHRAE 90.1-2019 for the commercial prototype) for each envelope component in the appropriate climate zone were used to set the level of insulation for the models "with insulation".

A total of 1,280 simulations were performed for the residential prototype and 480 simulations were performed for the commercial prototypes. Then, the total annual site energy use was extracted broken down by fuel type: electricity, natural gas, and fuel oil, and by end use (e.g., heating, cooling, lighting, etc.).

The results were aggregated for the residential prototype by assuming uniform distribution across the different climate zones, heating systems and foundation types. Similarly, the results for the commercial prototype were assumed to be uniformly distributed across the different climate zones to facilitate the comparison between the energy and carbon impacts from the different insulation scenarios. The total annual site energy savings were converted into source energy savings using source-site conversion ratios reported in literature for the different fuel types. The total annual source energy savings were then used to evaluate the annual GHG savings attributable to the insulation applied in the different scenarios. For this, the emission rates of natural gas and fuel oil were obtained from the Environmental Protection Agency database. For GHG emission rates attributed to electricity generation, the long-run emission rates provided by NREL's Cambium database were utilized. The US national average emission rates were chosen as a representation of emissions from the electricity generation. Three scenarios were selected from the Cambium database to reflect the projected impact of renewable energy (RE) costs on future emission rates: Low RE Costs, Medium RE Costs, and High RE Costs.

The focus of the study was to calculate the lifetime GHG emission reductions (kg CO_2e) per functional unit of insulation, assuming a lifespan of 75 years, for the different prototypes across the 16 climate zones.

In order to accommodate the forecasted future electrification of building energy systems, two scenarios were explored:

- Scenario 1: A conservative scenario that assumes that a uniform distribution of heating systems prevailing over the time horizon of the study (i.e., 75 years).
- Scenario 2: A scenario that assumes the full transition into heat pump heating systems.

These two scenarios provide bookend estimates of the energy and carbon impacts due to building insulation in a future that does not promote heating electrification versus another that assumes 100% penetration of heating heat pumps.

The key conclusions from this study can be summarized as follows:

- The distribution of normalized GHG savings in all climate zones demonstrates a positive impact of insulation on GHG emission reduction. This is primarily because of the significant effect of building envelope insulation on the heating and cooling demand of the living spaces.

- Buildings in colder climates were observed to have the highest average and median lifetime energy and carbon savings, highlighting the significant impact of envelope insulation on reducing the heating load during winter.
- The scenario involving the full transition into heat pump heating systems showed a drop in the normalized GHG savings per functional unit of insulation relative to the scenario with existing heating systems. This is primarily due to the improved efficiency of the heat pump relative to natural gas and fuel oil systems, resulting in lower annual energy consumptions.
- For the residential single-family home prototype, assuming a uniform distribution of existing heating systems, the median lifetime carbon savings were found to be 434 kg CO_2e/FU. The value ranged from 197 kg CO_2e/FU for cooling dominant climates to 861 kg CO_2e/FU for heating dominant climates. Assuming a future transition of the heating system into heat pumps, the median lifetime carbon savings were found to be 332 kg CO_2e/FU. The value ranged from 160 kg CO_2e/FU for cooling dominant climates to 1,128 kg CO_2e/FU for heating dominant climates.
- The commercial prototypes generally exhibited higher normalized emission savings per functional unit of insulation relative to the residential prototype. This indicates that the thermal insulation in commercial building envelopes has stronger impact on energy consumption reduction, yielding more GHG savings per unit of thermal insulation.
- For the commercial prototypes with natural gas heating systems, the median lifetime carbon savings were found to be 1,063 kg CO_2e/FU. The value ranged from 630 kg CO_2e/FU for cooling dominant climates to 1,668 kg CO_2e/FU for heating dominant climates. Assuming a future transition of the heating system into heat pumps, the median lifetime carbon savings were found to be 794 kg CO_2e/FU. The value ranged from 626 kg CO_2e/FU for cooling dominant climates to 1,185 kg CO_2e/FU for heating dominant climates.

1 Introduction

The insulation industry is interested in including a deemed value for the use-phase emission benefits of building thermal envelope insulation. Concurrently, the current Part B Product Category Rule (PCR) for Building Envelope Thermal Insulation is undergoing an update process and an opportunity for changes has opened. The current PCR includes an 'Additional Information' subsection that outlines how "insulation significantly reduces energy use in a building, thereby reducing the impact on the environment." This subsection is currently outside of the scope of mandatory rules for the development of Life Cycle Assessment (LCA) for Building Envelope Thermal Insulation and is not required as a part of the development of an Environmental Product Declaration (EPD).

As such, ICF was tasked to carry out a study to analyze the potential use-phase emission reductions realized through the installation of building envelope insulation for residential and commercial new construction. The study involved one prototype from the residential sector: single-family detached home, and six prototypes from the commercial sector: midrise apartment, medium office, retail strip mall, primary school, secondary school, and warehouse. The study investigated the lifecycle energy and carbon impact of applying building envelope thermal insulation to the seven prototypes in 16 climate zones: 1A, 2A, 2B, 3A, 3B, 3C, 4A, 4B, 4C, 5A, 5B, 5C, 6A, 6B, 7, and 8.

This report presents the modeling and analysis framework used to analyze the potential use-phase emission reductions realized through the installation of thermal insulation on the key envelope elements: exterior walls, attic or roof, and foundation.

2 Organization of the Report

The report contains the following remaining sections, beginning with an explanation of the study methodology and data inputs, and progressing through a presentation of the results and key conclusions.

- Methodology
- Results and Discussion
- Conclusions and Key Takeaways

3 Methodology

The study proceeded in the following steps:

3.1 Data Gathering

ICF utilized the national prototypical building energy models developed by Pacific Northwest National Laboratory (PNNL)[1]. These models were created originally to support the US Department of Energy's (DOE) determination of the impacts of changes to national-level energy codes (i.e., IECC and ASHRAE 90.1) on the energy use and carbon emission intensities in new construction

[1] https://www.energycodes.gov/prototype-building-models#Weather

residential and commercial buildings. PNNL developed these models using the EnergyPlus™ building energy simulation program, which was created by DOE and is widely regarded as the gold standard in building energy modeling. This national set of models includes two different residential building prototypes and 16 different commercial building prototypes across the different climate zones of the United States.

The current study investigated one residential prototypical building: a single-family detached home, and six commercial prototypical buildings: midrise apartment, medium office, retail strip mall, primary school, secondary school and warehouse across 16 climate zones: 1A, 2A, 2B, 3A, 3B, 3C, 4A, 4B, 4C, 5A, 5B, 5C, 6A, 6B, 7, and 8. Table 1 presents the list of representative cities and corrsponding weather station locations for the climate zones of interest to the current study.

For the residential single-family detached home, PNNL provides four different models for each climate zone that capture the different typical heating systems that can be installed to heat the home: electric resistance furnace, natural gas furnace, fuel oil furnace, and electric heat pump. Also, for each climate zone, PNNL provides building models for four different foundation types: vented crawlspace, heated basement, slab-on-grade, unheated basement and four different heating system types. The models reflecting the latest code level update (i.e., IECC 2021) were used.

For the commercial prototypes, PNNL provides only one representative model per building type for each climate zone. This study used the models representative of ASHRAE 90.1 – 2019 Standard requirements.

Table 1: List of Representative Cities, Weather Locations, and Heating Degree Days and Cooling Degree Days at 65°F Base Temperature for Climate Zones 3 and 5

Climate Zone	Represntative City	Weather Location	HDD_{65}	CDD_{65}
1A	Miami, Florida	Miami International airport, Florida	62	2589
2A	Tampa, Florida	Tampa/Mac Dill AFB, Florida	272	2039
2B	Tucson, Arizona	Tucson/Davis/Monthan AFB, Arizona	769	1812
3A	Atlanta, Georgia	Atlanta/Hartsfield Jackson International Airport, Georgia	2,498	2,099
3B	El Paso, Texas	El Paso International Airport, Texas	2,012	2,972
3C	San Diego, California	San Diego/Brown Field Municipal Airport, California	1,377	763
4A	New York, New York	New York/John Kennedy International Airport, New York	2,645	587
4B	Albuquerque, New Mexico	Albuquerque International Sunport, New Mexico	2,152	827
4C	Seattle, Washington	Seattle/Tacoma International Airport, Washington	2,567	126
5A	Buffalo, New York	Buffalo Niagara International Airport, New York	6,242	769
5B	Denver, Colorado	Denver/Aurora/Buckley AFB, Colorado	5,737	832
5C	Port Angeles, Washington	Port Angeles/William R Fairchild International Airport, Washington	5,488	20
6A	Rochester, Minnesota	Rochester International Airport, Minnesota	4,322	303
6B	Great Falls, Montana	Great Falls International Airport, Montana	4,222	233

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Climate Zone	Represntative City	Weather Location	HDD_{65}	CDD_{65}
7	International Falls, Minnesota	International Falls International Airport, Minnesota	5,507	165
8	Fairbanks, Alaska	Fairbanks International Airport, Alaska	7,426	37

ICF used TMY3 weather files for the climate zones listed in Table 1.[2] The TMY3 files are typical meterological year data derived from hourly weather data for 30 years (1991-2005) in the ISD (US NOAA's Integrated Surface Database) using the TMY/ISO 15927-4:2005 methodologies.

3.2 Prototypical Building Model Setup

This section demonstrates the setup of the residential and commercial building models.

3.2.1 Residential Prototype: Single-family Detached Home

Table 2 displays the key building characteristics utilized in the PNNL prototypical models for the single-family detached home.

Table 2: Prototypical Building Characteristics for Single-Family Detached Home

Prototype	Single-Family Home (2-story)			
Foundation Type	Heated Basement	Vented Crawlspace	Slab-on-Grade	Unheated Basement
Conditioned Floor Area (ft²)	3,565	2,377		
HVAC Systems	• Air Conditioning: DX Cooling Coil with rated COP=4.0 • Heating: 4 Systems ○ Electric Resistance ○ Gas Furnace (80% Efficiency) ○ Oil Furnace (78% Efficiency) ○ Heat Pump (rated COP=3.7 with back-up electric resistance heating)			

The study explored the impact of the following five scenarios, shown in Table 3, on the energy and GHG emissions over an assumed lifetime of the insulation materials of 75 years. The 75-year lifetime was selected based on recommendation from ULE Standard 10010.[3] Note that "R" in the scenario label stands for "Residential", and it should not be confused for the R-value of the insulation material. Similarly, "C" in the scenario label stands for "Commercial". Throughout this report, the R-value of the insulation will be hyphened to distinguish it from the simulated scenarios for the residential prototype.

[2] https://www.energycodes.gov/prototype-building-models

[3] UL Environment Standards (2022). Product Category Rules for Building Related Products and Services, Part A: Life Cycle Assessment Calculation Rules and Report Requirements (https://www.shopulstandards.com/ProductDetail.aspx?productId=ULE10010_6_S_20220328)

Table 3: Simulated Scenarios for Residential and Commercial Prototypes

Scenario	Description	Scenario	Description
Residential Prototypes:		**Commercial Prototypes:**	
R0	No Insulation	C0	No Insulation
R1	Exterior Wall Insulation	C1	Exterior Wall Insulation
R2	Foundation Insulation	C2	Slab Perimeter Insulation
R3	Attic Floor Insulation	C3	Roof Insulation
R4	Whole Home Insulation	C4	Whole Building Insulation

These scenarios were designed to enable the assessment of the effect of thermal insulation of each envelope element (i.e., exterior wall, foundation and attic or roof) on the lifetime emission savings.

Recall that the PNNL models for the prototypical buildings capture the state of the envelope insulation that is conforming with the respective building codes and standards. As such, for R0 and C0 scenarios (i.e., uninsulated building), the heat transfer (UA) calcuation method detailed in ResCheck[4] and ComCheck[5] Technical Support Documents (TSDs) was used to estimate the R-value for the enevlope elements with no insulation for residential and commercial prototypes, respectively. The PNNL models were then adjusted to model the unisulated envelope scenario. This scenario served as the baseline for the energy and emissions savings calculations. To clarify, Table 4 shows the construction layers of the exterior wall of the single-family home prototype. This study assumes a wood-frame exterior wall comprising 2x4 studs 16-inch on center (O.C.). This translates into a framing factor (FF) of 25%[6]. Two parallel heat flow paths were developed to calculate the effective R-value of the baseline exterior wall assembly in the absence of thermal insulation. The calculation indicates an effective assembly R-value of 2.43. The energy model for R0 scenario is modified accordingly to map this value on the exterior wall assembly.

[4]https://www.energycodes.gov/sites/default/files/2019-09/BECP_REScheck_TSD465_Mar2019.pdf

[5] https://www.energycodes.gov/sites/default/files/2019-09/BECP_COMcheck_TSD391_Sep2012.pdf

[6] REScheck Technical Support Document (2019) - https://www.energyco10.57des.gov/sites/default/files/2019-09/BECP_REScheck_TSD465_Mar2019.pdf

Table 4: R-Values of Construction Layers of Exterior Wall through Studs Path and Cavity Path (Starting from the Outer Layer) for R0 Scenario (No Insulation)

Construction Layer	R0 Scenario	
	Studs Path	Cavity Path
Plywood Sheathing[6]	0.59	0.59
Continuous Insulation	0.00	0.00
Wood Studs (2x4 studs 16" O.C.)[6]	4.38	1.01
½-inch Gypsum Board[6]	0.45	0.45
Total Path R-value	**5.42**	**2.05**
Effective R-value (considering the framing factor)	$\frac{\mathbf{5.42 \times 2.05}}{\mathbf{5.42 \times (1 - 25\%) + 2.05 \times 25\%}} = \mathbf{2.43}$	

Building enevlope R-values leveraged in the building energy simulations across climate zones for single-family home prototype are summarized in Table 5. Further details on the building enevlope R-values utilized in the building simulations across all climate zones are described in Appendix A.

Table 5: Baseline and IECC 2021 Assembly Effective R-Values for Various Envelope Elements in Different Climate Zones (Residential Prototype)

	Assembly Effective R-value (ft²·F·h/Btu)								
Envelope Element	**Baseline (No Insulation)**	**IECC 2021 Insulation Level**							
	All	**CZ1**	**CZ2**	**CZ3**	**CZ4**	**CZ5**	**CZ6**	**CZ7**	**CZ8**
Exterior Wall	2.43	10.67	10.67	15.64	19.62	19.62	19.62	19.62	19.62
Crawlspace Wall	0.44	0.44	0.44	5.44	10.44	15.44	15.44	15.44	15.44
Heated Basement Wall	1.60	1.60	1.60	6.60	11.60	16.60	16.60	16.60	16.60
Crawlspace and Unheated Basement Ceiling	5.16	14.32	14.32	19.54	19.54	29.00	29.00	35.80	35.80
Slab Perimeter*	0.00	0.00	0.00	10.00	10.00	10.00	10.00	10.00	10.00
Attic Floor	1.53	26.53	37.10	41.16	41.16	41.16	41.16	41.16	41.16

*** Slab perimeter insulation is representative of the installed insulation not the assembly insulation. The tabulated values were applied only to homes with heated basement or slab-on-grade foundations, as the heating and cooling demands of these homes are expected to be influenced by the slab insulation.**

3.2.2 Commercial Prototypes: Midrise Apartment, Medium office, Retail strip mall, Primary school, Secondary school, and Warehouse,

The prototypical building characteristics for the six commercial prototypes under study are outlined in Table 6.

Table 6: Prototypical Building Characteristics for Commercial Prototypes

Prototype	Retail Strip Mall	Medium Office	Primary School	Secondary School	Warehouse	Midrise Apartment
Building Characteristics	• Conditioned area: 22,500 ft^2 • 1 floor	• Conditioned area: 53,600 ft^2 • 3 floors	• Conditioned area: 73,958 ft^2 • 1 floor	• Conditioned area: 210,886 ft^2 • 2 floors	• Conditioned area: 52,044 ft^2 • 1 floor	• Conditioned area: 30,397 ft^2 • 4 floors
HVAC Systems	• Packaged Rooftop System: ○ AC: Multispeed DX Cooling Coil with rated COP=3.8 ○ Heating: Gas Furnace (81% Efficiency)	• Packaged Air Unit per floor including: ○ AC: 2-speed DX Cooling Coil with rated COP=3.4 ○ Heating: Gas Furnace (81% Efficiency + Electric Resistance Reheat)	• Packaged rooftop VAV with reheat: ○ AC: 2-speed DX Cooling Coil with rated COP=3.4 ○ Heating: Gas Furnace (81% Efficiency)	• VAV with reheat: ○ AC: Multispeed DX Cooling Coil with rated COP=3.4 ○ Heating: Gas Furnace (81% Efficiency)	• Packaged Rooftop System: ○ AC: 2-speed DX Cooling Coil with rated COP=3.8 ○ Heating: Gas Furnace (81% Efficiency)	• Packaged Rooftop System: ○ AC: single speed DX Cooling Coil with rated COP=3.9 ○ Heating: Gas Furnace (81% Efficiency)

Building enevlope R-values leveraged in the building energy simulations across climate zones for commercial prototypes are summarized in Table 7. Table 8 presents the F-factor values for slab perimeter insulation for commercial prototypes in various climate zones. Further details on the building enevlope R-values utilized in the building simulations across all climate zones are described in Appendix A.

Table 7: Baseline and ASHRAE 90.1-2019 Assembly Effective R-Values for Various Envelope Elements in Different Climate Zones (Commercial Prototypes)

	Assembly Effective R-value ($ft^2.F.h/Btu$)								
Envelope Element	**Baseline (No Insulation)**	**ASHRAE 90.1-2019 Insulation Level**							
	All	**CZ1**	**CZ2**	**CZ3**	**CZ4**	**CZ5**	**CZ6**	**CZ7**	**CZ8**
Exterior Wall (Non-Residential)*	1.43	7.22	11.06	12.13	14.77	17.33	19.56	19.56	26.18
Exterior Wall (Residential)**	1.43	7.22	14.77	14.77	14.77	17.33	19.56	22.96	26.18
Exterior Wall (Warehouse Office Space)***	1×10^{-4}	9.90	9.90	9.90	15.93	19.26	19.26	21.99	24.91
Exterior Wall (Warehouse Storage Space)****	1×10^{-4}	2.10	5.44	5.44	5.44	9.90	9.90	13.15	15.93
Roof (Non-Residential)	1×10^{-4}	20.05	24.86	24.86	30.47	30.47	30.47	34.93	34.93
Roof (Residential)	1×10^{-4}	24.81	24.81	24.81	30.47	30.47	30.47	34.93	34.93
Roof (Warehouse Office Space)	1×10^{-4}	23.61	23.61	23.61	26.24	26.24	31.48	33.68	37.68
Roof (Warehouse Storage Space)	1×10^{-4}	7.92	9.64	9.64	11.41	11.41	15.89	26.24	26.24

*** Non-residential apply to all prototypes except mid-rise apartment buildings and warehouse office spaces.**

**** Residential applies only to mid-rise apartment buildings.**

***** The prototypical model for the warehouse office space assumes the envelope to be of "Metal Building" type, whereas other prototypes are assumed to have a "Steel Framed" envelope.**

****** ASHRAE 90.1 provides specific insulation requirements for semi-heated spaces (such as the storage area of the warehouse).**

Table 8: Baseline and ASHRAE 90.1-2019 F-factor for Slab Perimeter Insulation in Different Climate Zones (Commercial Prototypes)

	F-factor (Btu/h.ft.°F)								
Commercial Prototype	**Baseline (No Insulation)**	**ASHRAE 90.1-2019 F-factor**							
	All	**CZ1**	**CZ2**	**CZ3**	**CZ4**	**CZ5**	**CZ6**	**CZ7**	**CZ8**
Non-Residential	0.73	0.73	0.73	0.73	0.52	0.52	0.51	0.51	0.43
Residential	0.73	0.73	0.73	0.54	0.52	0.51	0.43	0.43	0.42
Warehouse Office Space	0.73	0.73	0.73	0.73	0.52	0.52	0.51	0.43	0.43
Warehouse Storage Space	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.54

3.3 Model Simulations

Prior to running the final simulations, the PNNL models were simulated unaltered. ICF ran a total of 1,760 simulations:

A. Residential Prototype – Single-Family Detached Home

16 Climate Zones x 4 Heating Systems x 4 Foundation Types x 5 Scenarios = 1,280 Simulations

B. Commercial Prototypes – Midrise Apartment, Medium Office Building, Retail Strip Mall, Primary School, Secondary School and Warehouse

16 Climate Zones x 6 Prototypes x 5 Scenarios = 480 Simulations

3.4 Results Post-Processing

The results from the simulations were filtered to extract the annual site total energy use per building broken down by fuel type (i.e., electricity, natural gas, and fuel oil) and end use (i.e., heating, cooling, lighting, etc.).

In order to properly evaluate the GHG emission savings attributed to envelope insulation, source energy use was derived from site energy use using the source-site ratios listed in Table 9.

Table 9: Source-Site Ratios of Different Fuel Types[7]

Fuel Type	Source-Site Ratio
Electricity	2.95
Natural Gas	1.09
Fuel Oil	1.10

[7] PNNL, Energy Savings Analysis: 2021 IECC for Residential Buildings (2021) - https://www.energycodes.gov/sites/default/files/2021-07/2021_IECC_Final_Determination_AnalysisTSD.pdf

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For the residential prototypes, the current analysis assumes an equal distribution of the 16 prototypes (i.e., 4 heating systems x 4 foundation types) in each climate zone. Such an assumption was made due to absence of reliable data for future distribution of homes with various heating systems and foundation types. Utilizing this assumption, however, results in a conservative estimate of emissions savings (i.e., lower emissions savings than if the current market distribution of heating system types – predominantly natural gas fueled - was used). Two scenarios were then explored to examine the effect of heating system electrification in the future:

1. **Scenario 1 – Uniform Distribution of Existing Heating Systems:** assumes an equal distribution of the four heating system types (i.e., 25% share for each type), prevailing over the time horizon of the study (i.e., 75 years).
2. **Scenario 2 – 100% Heat Pump Systems:** assumes a full transition into heat pump heating systems. As such, this scenario only presents the results for the single-family home prototype with heat pump heating systems.

Similarly for the commercial prototypes, the current analysis assigned equal weights to all six prototypes in each climate zone. Two scenarios were then explored to examine the effect of heating system electrification in the future:

1. **Scenario 1 – Existing Heating Systems:** assumes that the existing natural gas space and water heating systems prevail over the time horizon of the study (i.e., 75 years).
2. **Scenario 2 – 100% Heat Pump Systems:** assumes the full transition into heat pump heating systems. This scenario converts the natural gas consumption for space and water heating into the equivalent electricity consumption by electric heat pump systems.

The true results are expected to be a smooth transition between Scenarios 1 and 2. However, with the ever-changing dynamics of climate-action policies, fuel prices and technology costs, predicting the phase out rate of fossil fuel heating and the proliferation rate of heat pumps is extremely challenging.

3.5 GHG Accounting

ICF evaluated the annual GHG emission savings using the annual source energy savings and the fuel specific GHG emission rates.

For electricity consumption, the long-run emission rates provided by NREL's Cambium database[1] were utilized. Upon consultation, the national average US emission rates were chosen as a conservative representation of emissions from the electricity generation. Three scenarios were selected from the Cambium database to reflect the projected impact of renewable energy (RE) costs on emission rates: Low RE Costs, Medium RE Costs, and High RE Costs. Table 10shows the national average US electricity emission rates generated by Cambium for three RE cost scenarios. Since the Cambium database provides emission rate estimates only up to 2050, this study assumes the values in 2050 to prevail over the remainder of the study's time horizon (up to 2098).

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

Linear interpolation was applied between the datapoints in Table 10 to obtain the emission rates for the intermediate years.

Table 10: Electricity Emission Rates for Three Scenarios: Low RE Cost, Medium RE Cost, and High RE Cost

Year	Electricity Emission Rate (kg CO_2e/MWh)		
	Low RE Cost	Medium RE Cost	High RE Cost
2024	541.9	554.4	512.4
2026	484.2	497.3	471.8
2028	426.5	440.2	431.2
2030	311.0	325.9	349.9
2035	195.5	211.6	268.7
2040	120.5	153.9	182.1
2045	117.0	148.0	184.5
2050	134.3	118.3	170.5

For natural gas and fuel oil consumptions, the emission rates were assumed to be 5.30 kg CO_2e/therm and 10.24 kg CO_2e/gallon, respectively[2].

The current study focuses on the calculation of the lifetime carbon savings due insulation of the various envelope elements normalized by the functional units of the respective insulation. According to the Product Category Rule, the insulation functional unit (FU) is defined as 1.0 m^2 of the insulation material with an RSI = 1.0 m^2.K/W. As such, the value of total functional units in each envelope element's insulation was calculated using:

$$Functional\ Units\ [m^2 - RSI] = A_{net} \times RSI_{continous} + A_{net} \times (1 - FF\%) \times RSI_{cavity}$$

Where, A_{net} refers to the net surface area in m^2 of the envelope element to which the insulation is applied. $FF\%$ is the framing factor relevant to framed constructions. $RSI_{continous}$ and RSI_{cavity} refer to the RSI values of the continuous and cavity insulations, respectively.

First, the site annual energy savings by fuel type were calculated for each insulation scenario by subtracting the site annual energy consumption of the insulated case from that of the baseline case. For example, the site annual electricity savings for scenario R1 (exterior wall insulation only) was calculated using the following equation:

$$Site\ Annual\ Electricity\ Savings = Site\ Annual\ Electricity\ Consumption_{R0} - Site\ Annual\ Electricity\ Consumption_{R1}$$

Second, the lifetime GHG savings were calculated using the following equation:

$$Lifetime\ GHG\ Savings = \sum_{75\ years} Site\ Annual\ Electricity\ Savings \times Annual\ Electricity\ Emission\ Rate + Site\ Annual\ Natural\ Gas\ Savings \times Natural\ Gas\ Emission\ Rate \times 75\ years + Site\ Annual\ Fuel\ Oil\ Savings \times Fuel\ Oil\ Emission\ Rate \times 75\ years$$

[2] See the EPA webpage at https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

It is expected that the sum of the lifetime GHG savings from scenarios R1, R2 and R3 (i.e., insulation on individual envelope elements) will not align with the lifetime GHG savings from scenario R4 (i.e., whole building insulation) due to the unaccounted-for interactive effects from insulating all envelope elements simultaneously. As such, the results from scenarios R1, R2 and R3 were scaled to match those from scenario R4, thereby providing the proportional contributions of insulation on the individual envelope elements to the total savings from the whole building insulation case. A similar process is applied to the results for the commercial prototypes to align savings from scenarios C1, C2 and C3 with those from scenario C4.

For each prototype, the process above provided three values of lifetime GHG savings representing the contribution of exterior wall insulation, foundation insulation and attic floor or roof insulation to the total savings from the whole building insulation case. Each of these values was normalized by the respective functional units of insulation.

The approach for calculating the normalized lifetime carbon savings (kg CO_2e/functional unit) is explained in Table 11 and Table 12 for a single-family home prototype in climate zone 8 with heated basement and heat pump heating system.

Table 11: Calculation of Lifetime Carbon Savings for Single-Family Home Prototype in CZ 8 with Heated Basement and Heat Pump Heating System

Insulation Scenario	Total Site Energy (kBtu)	Site Energy Savings (kBtu)	Lifetime GHG Savings (metric tons CO_2e)*
No Insulation	342,919	0	0
Wall Insulation	239,665	103,254	1,198
Foundation Insulation	331,825	11,094	129
Attic Floor Insulation	283,301	59,618	692
Whole Home Insulation	155,466	187,453	2,175

*** Using electricity emission rates for the medium RE cost scenario**

Table 12: Calculation of Lifetime Carbon Savings Per Functional Unit of Insulation for Single-Family Home Porotype in CZ 8 with Heated Basement and Heat Pump Heating System

Insulation Scenario	Adjusted Lifetime GHG Savings (metric tons CO_2e)*	Functional Units (FUs)	Normalized Lifetime GHG Savings (kg CO_2e per FU)
Wall Insulation	1,291	556	**2,322**
Foundation Insulation	139	274	**507**
Attic Floor Insulation	745	789	**945**
Whole Home Insulation	2,175	1,618	**1,344**

*** Using electricity emission rates for the medium RE cost scenario**

The following section provides visualization of the highlighted values in Table 12 for all the prototypes investigated in the present study.

4 Results and Discussion

This section discusses the results from the simulations of the residential and commercial prototypes.

4.1 Residential Prototype: Single-family Detached Home

4.1.1 Scenario 1: Uniform Distribution of Existing Heating Systems

This scenario assumes an equal distribution of the four heating system types (i.e., 25% share for each type), prevailing over the time horizon of the study (i.e., 75 years). Figure 1 shows the impact of insulation of individual envelope elements on emission savings per functional unit across all 16 climate zones. The datapoints were aggregated and presented together to the far right of the figure, labelled “All”. Table 13 summarizes the key statistical values for the normalized GHG savings presented in Figure 1.

It is observed that the average and median values of the normalized lifetime GHG savings in all climate zones indicate a positive impact of insulation on GHG emission reduction. It is seen that the impact of insulation is more pronounced in colder climates, showing the highest average and median savings CZ 8. This is primarily attributed to the rather significant impact of envelope insulation on reducing the heating load during winter. The median lifetime savings were found to range from 127 to 957 kg CO_2e/FU. Aggregating all the results, it is found that the median saving was 400 kg CO_2e/FU.

It is seen that the lifetime carbon savings are predominantly driven by the exterior wall insulation (green dots), followed by the attic floor insulation (orange dots). This is primarily due to the larger surface area of the exterior wall compared to that of the attic floor, resulting in greater impact on the heating and cooling loads of the building. The foundation insulation (magenta dots) is seen to have the weakest influence on the carbon savings except in the scenarios with heated basement and slab on grade in colder climate zones.

It is worth noting that a few datapoints on the figure show negative normalized savings, indicating increased consumption after applying the insulation. Upon further investigation, it was observed that the negative savings were attributed solely to foundation insulation. These negative impacts were found to be even more pronounced in moderate climates (CZ 3-5). This is likely due to one or a combination of the following reasons:

- The foundation insulation shields the free heating and cooling capacity from the surrounding soil.
- The EnergyPlus software applies several simplifying assumptions on the heat transfer dynamics between the foundation’s envelope and the surrounding soil. This likely results in inaccurate estimates for the impact of foundation insulation on the total energy consumption.

Focusing on the impact of insulation on the entire envelope, Figure 2 illustrates the ratio between the lifetime carbon savings from the whole home insulation and the total functional units of insulation in all elements comprising the building’s envelope.

It is observed that whole home insulation always results in positive lifetime carbon savings, indicating the dominant impact of exterior wall and attic floor insulation relative to foundation insulation. In addition, the figure demonstrates smaller variance in data, with the median savings ranging between 197 to 861 kg CO_2e/FU (Table 14).

4.1.2 Scenario 2: 100% Heat Pump Systems

This scenario assumes the full transition into heat pump heating systems. As such, this scenario only presents the results for the single-family home prototype with heat pump heating systems. It explores a hypothesized future where all single-family homes with fossil-fuel heating systems transition to heat pump space and water heating systems.

Figure 3 presents a subset of the datapoints presented in Figure 1 that represent the single-family home prototype with heat pump system. It is expected that switching the heating system to a heat pump will result in a drop in the total energy consumption of the home, thereby reducing the potential savings from envelope insulation. It is seen that Figure 3 follows a trend similar to that in Figure 1. However, the normalized GHG savings values for Scenario 2 are generally lower than corresponding values in Scenario 1. Table 15 summarizes the key statistical values for the normalized GHG savings presented in Figure 3.

It is seen that the median savings range between 104 to 901 kg CO_2e/FU, with an aggregate value of 354 kg CO_2e/FU. Similar to Scenario 1, it is observed that, when the normalized carbon savings are visualized for the whole home insulation (Figure 4), the savings exhibited a tighter variance across the different prototypes and climate zones. Table 16 shows the median savings ranged between 160 to 1,128 kg CO_2e/FU, with an aggregate value of 332 kg CO_2e/FU.

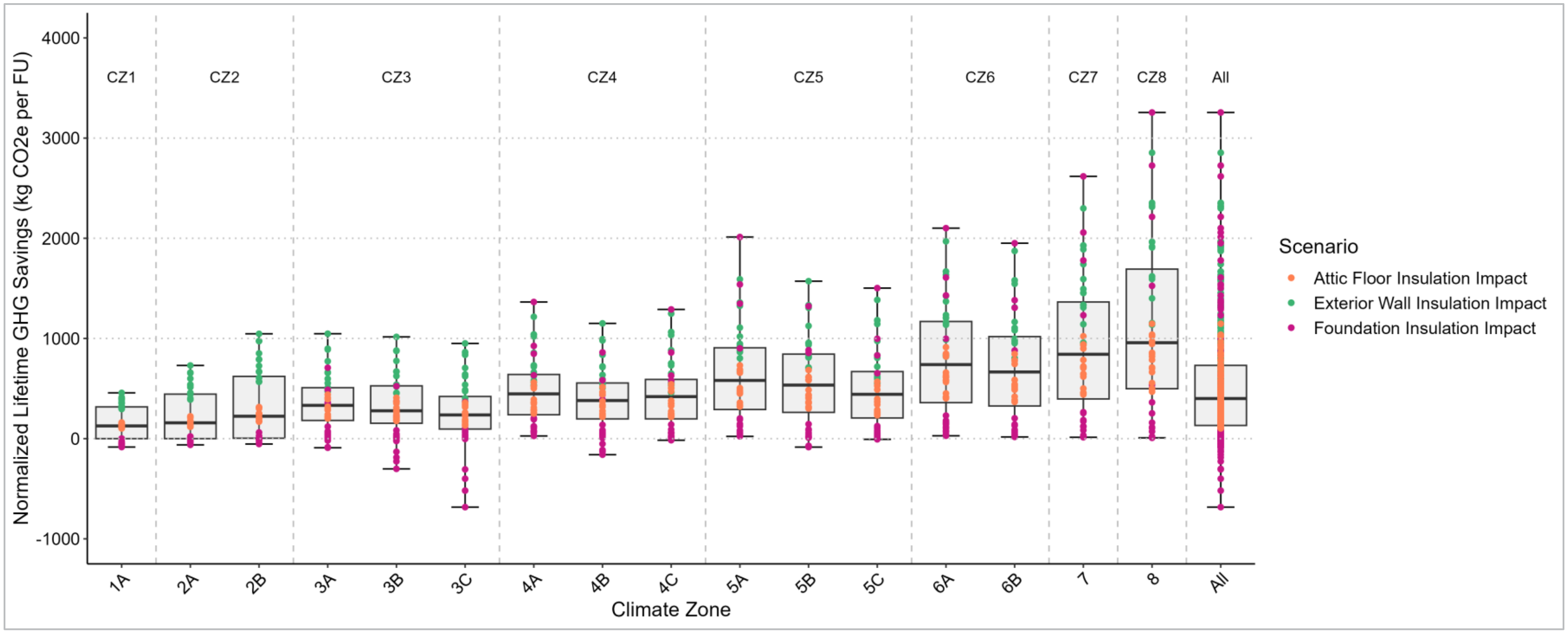

Figure 1: Distribution of Normalized Lifetime GHG Savings per Functional Unit of Insulation in Individual Envelope Elements (Residential Prototypes – Scenario 1)

Table 13: Summary of Key Values for Normalized Lifetime GHG Savings per Functional Unit in Individual Envelope Elements (Residential Prototypes – Scenario 1)

Quartile values	1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8	All
Minimum	-84	-62	-54	-91	-302	-684	27	-160	-16	23	-84	-7	29	17	14	8	-684
1st Quartile	0	0	1	141	107	81	217	158	160	231	184	153	273	244	308	495	131
Median	127	158	224	332	278	237	447	381	419	581	535	443	739	666	842	957	400
Average	152	225	333	357	323	259	477	394	437	643	558	487	787	709	918	1,125	512
2nd Quartile	320	447	651	509	534	456	656	574	616	918	852	702	1,192	1,060	1,424	1,836	731
Maximum	457	730	1,047	1,047	1,016	951	1,364	1,151	1,290	2,012	1,572	1,503	2,101	1,951	2,618	3,256	3,256

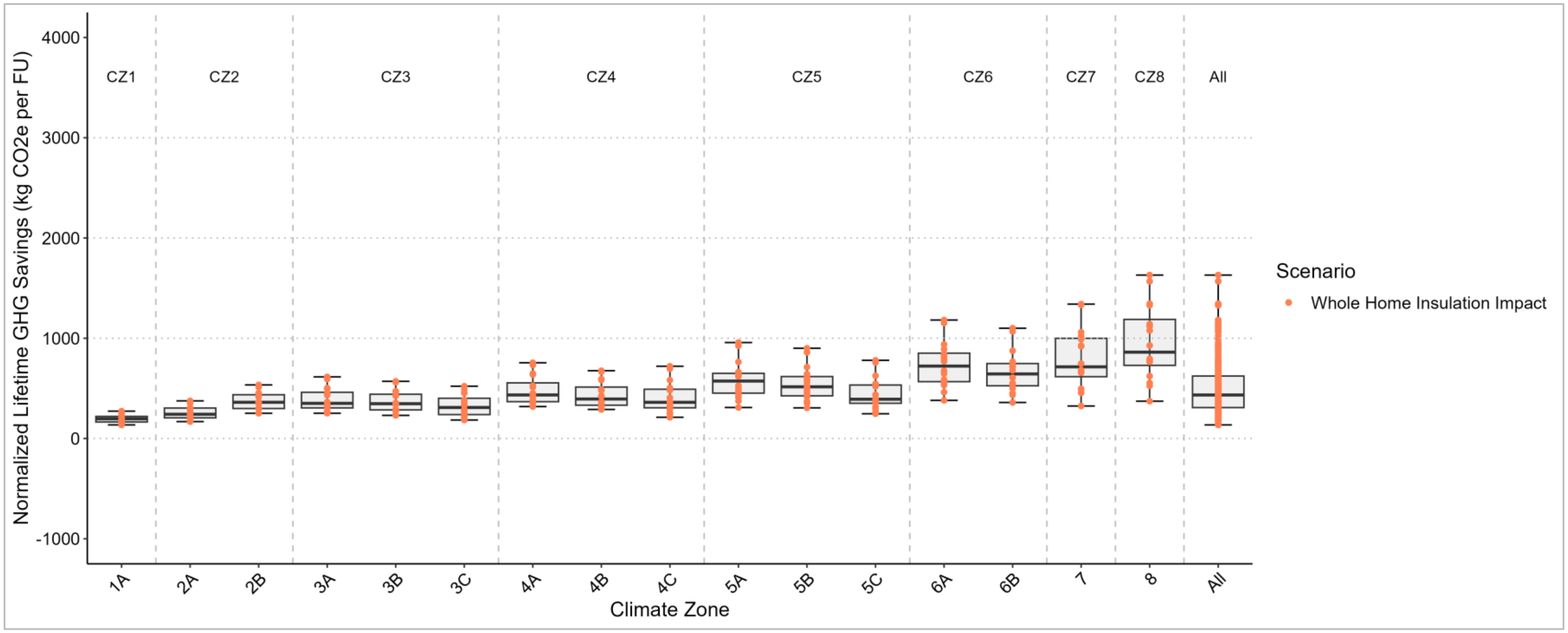

Figure 2: Distribution of Normalized Lifetime GHG Savings per Unit Functional Unit of Insulation in Whole Home Envelope (Residential Prototypes – Scenario 1)

Table 14: Summary of Key Values for Normalized Lifetime GHG Savings per Functional Unit in Whole Home Envelope (Residential Prototypes – Scenario 1)

Quartile values	1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8	All
Minimum	136	169	252	252	231	185	319	290	212	309	306	247	380	359	324	372	136
1st Quartile	154	201	299	284	280	228	359	322	298	440	420	328	555	509	536	658	307
Median	197	242	361	351	347	309	434	394	361	573	516	392	722	644	715	861	434
Average	193	255	371	386	369	323	478	435	411	583	544	451	737	666	798	958	497
2nd Quartile	221	305	447	484	458	436	610	561	501	659	634	542	877	760	1,016	1,282	625
Maximum	273	376	535	615	570	522	756	676	721	957	900	780	1,182	1,100	1,340	1,630	1,630

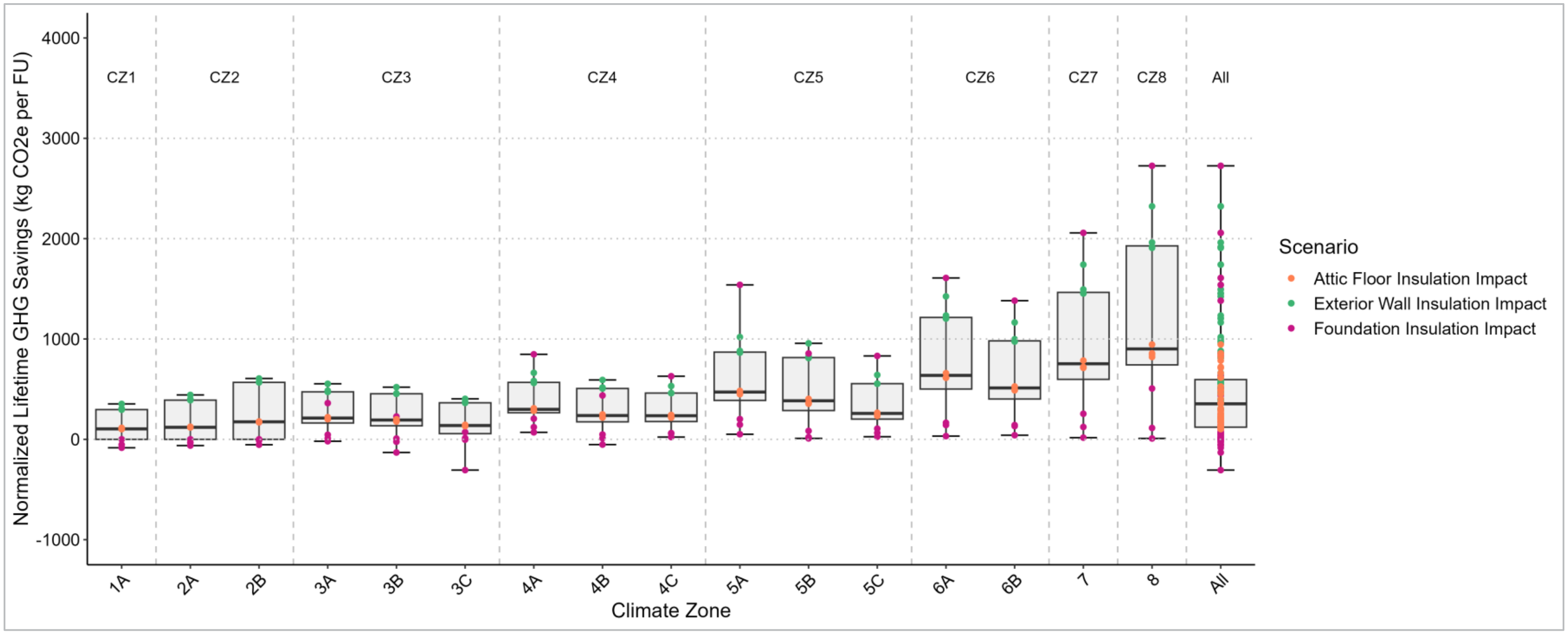

Figure 3: Distribution of Normalized Lifetime GHG Savings per Functional Unit of Insulation in Individual Envelope Elements (Residential Prototypes – Scenario 2)

Table 15: Summary of Key Values for Normalized Lifetime GHG Savings per Functional Unit in Individual Envelope Elements (Residential Prototypes – Scenario 2)

Quartile values	1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8	All
Minimum	-84	-62	-54	-19	-131	-307	70	-52	23	51	9	26	32	41	17	9	-307
1st Quartile	0	0	0	85	50	27	226	90	100	264	152	138	277	229	369	585	121
Median	104	120	175	212	193	138	299	237	235	471	384	258	637	512	753	901	354
Average	129	168	245	268	226	153	399	290	300	618	489	361	793	651	961	1,244	456
2nd Quartile	299	393	569	474	454	368	577	508	462	877	822	555	1,227	992	1,484	1,950	603
Maximum	353	443	607	554	520	404	847	592	629	1,539	957	831	1,608	1,382	2,058	2,726	2,726

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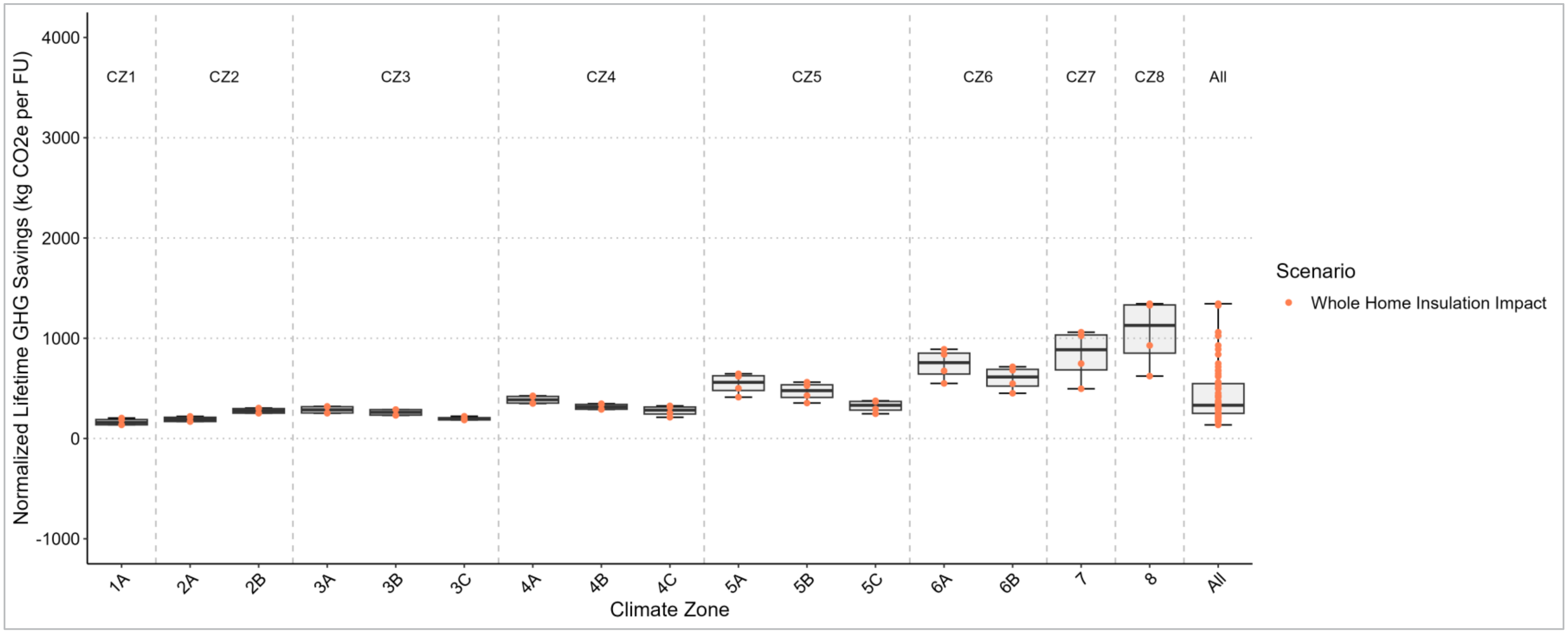

Figure 4: Distribution of Normalized Lifetime GHG Savings per Unit Functional Unit of Insulation in Whole Home Envelope (Residential Prototypes – Scenario 2)

Table 16: Summary of Key Values for Normalized Lifetime GHG Savings per Functional Unit in Whole Home Envelope (Residential Prototypes – Scenario 2)

Quartile values	1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8	All
Minimum	136	169	252	252	231	185	349	290	212	412	354	247	550	451	496	622	136
Quartile 01	136	169	252	253	231	185	350	291	223	434	373	259	581	475	559	699	248
Median	160	189	275	286	261	195	386	315	283	560	478	331	757	614	885	1,128	332
Average	165	192	277	286	260	199	387	317	276	545	468	322	738	599	832	1,056	432
Quartile 02	199	218	302	319	288	217	424	345	322	639	553	374	877	707	1,051	1,340	549
Maximum	204	221	304	320	289	222	426	347	325	646	562	376	890	715	1,060	1,344	1,344

4.2 Commercial Prototypes

Similar figures were developed for the commercial prototypes in different climate zones.

4.2.1 Scenario 1: Existing Heating Systems

This scenario assumes that the existing natural gas space and water heating systems prevail in all six commercial prototypes over the time horizon of the study (i.e., 75 years).

Figure 5 to Figure 8 show the impact of building envelope insulation on emission savings per functional unit across all 16 climate zones. Table 17 to Table 20 provide summaries of the key statistical values for the normalized lifetime GHG savings in commercial prototypes.

It is seen that the lifetime carbon savings are predominantly driven by the roof insulation (orange dots), followed by the exterior wall insulation (green dots). This is primarily due to the larger surface area and insulation levels of the roof compared to that of the exterior wall, resulting in greater impact on the heating and cooling loads of the building. The slab perimeter insulation (magenta dots) is seen to have the weakest influence on the carbon savings. This is likely because the slab insulation was only applied to the perimeter, limiting its effect to a smaller surface area of the foundation.

Similar to residential prototypes, it is observed that the median values of the normalized GHG savings in all climate zones indicate a positive impact of insulation on GHG emission reduction. It is seen that the impact of insulation is more pronounced in colder climates, showing the highest average and median savings CZ 8. However, compared to the residential prototypes, the commercial prototypes generally exhibit higher normalized emission savings per unit functional unit of insulation. This indicates that the thermal insulation in commercial building envelopes has stronger impact on energy consumption reduction, yielding more GHG savings per unit of thermal insulation.

Figure 5 and Figure 7 are shown to display fewer datapoints with negative normalized savings. This is because in all commercial prototypes the foundation insulation was only applied to the perimeter of the slab, resulting in a slight increase in the heating and cooling consumptions in the ground floor, thereby slightly increased emissions in the cases with insulated slab perimeter.

For the effect of individual envelope elements' insulation, the median savings were in the range of 485 to 1,053 kg CO_2e/FU, with an aggregate value of 587 kg CO_2e/FU (Table 17). On the other hand, the effect of entire building insulation results in median carbon savings in the range of 630 to 1,668 kg CO_2e/FU, with an aggregate value of 1,063 kg CO_2e/FU (Table 18).

4.2.2 Scenario 2: 100% Heat Pump Systems

This scenario explores a hypothesized future where all commercial prototype buildings with fossil-fuel heating systems transition to heat pumps. Such a scenario was compiled by estimating the heating loads from Scenario 1, then calculating the heat pump electricity consumption assuming a seasonal average COP of 3.3 for all climate zones. Although water heating system is expected to be insensitive to envelope insulation, it is evident that the future is trending towards a full transition into heat pump systems for both space and water heating. As such, the current analysis evaluated the electricity consumption of a heat pump for water heating assuming an average COP of 3.3. This enabled the adjustment of the normalized emission savings in Scenario 1 to provide the results for Scenario 2, shown in Figure 7 and Figure 8.

It is seen that the normalized GHG savings values for Scenario 2 are generally lower than corresponding values in Scenario 1. This is attributed to the significant enhancement in energy efficiency associated with switching the heating system to a heat pump.

For the effect of individual envelope elements' insulation, the median savings were in the range of 470 to 706 kg CO_2e/FU, with an aggregate value of 416 kg CO_2e/FU (Table 19). On the other hand, the effect of entire building insulation results in median carbon savings in the range of 626 to 1,185 kg CO_2e/FU, with an aggregate value of 794 kg CO_2e/FU (Table 20).

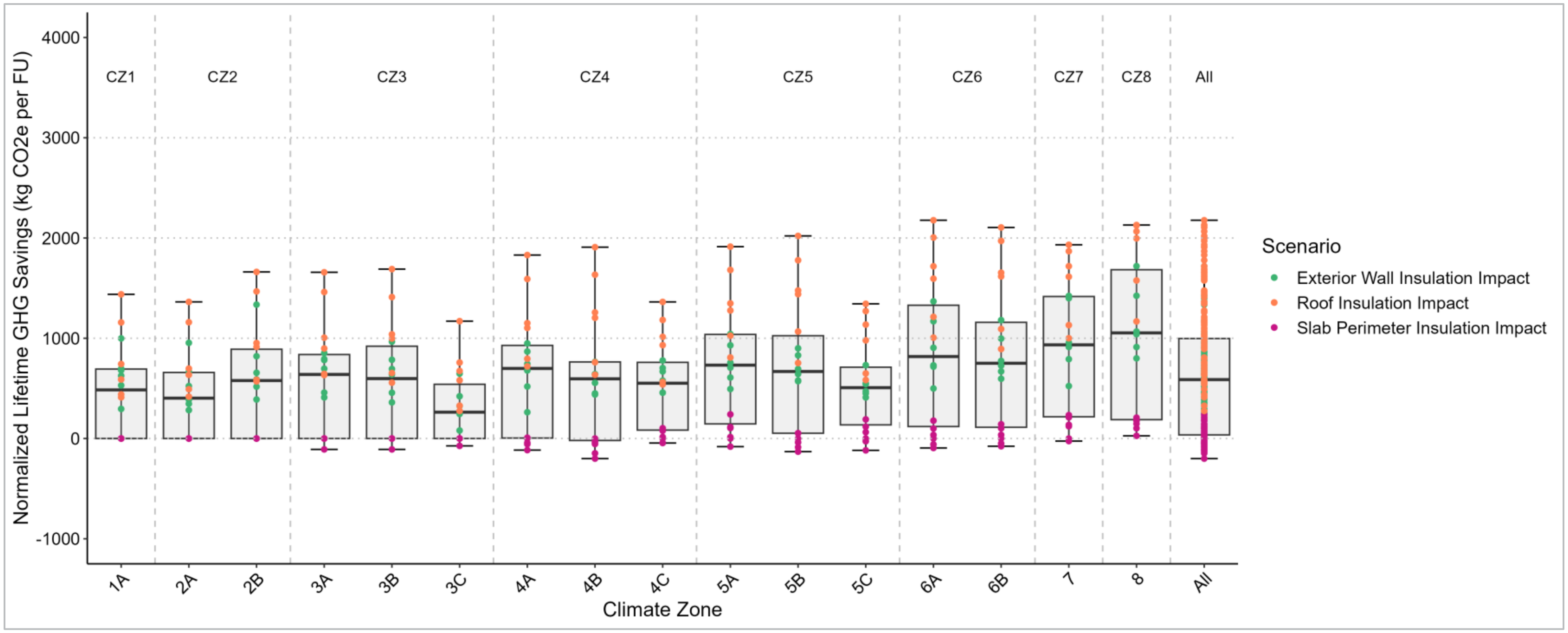

Figure 5: Distribution of Normalized Lifetime GHG Savings per Functional Unit of Insulation in Individual Envelope Elements (Commercial Prototypes – Scenario 1)

Table 17: Summary of Key Values for Normalized Lifetime GHG Savings per Functional Unit in Individual Envelope Elements (Commercial Prototypes – Scenario 1)

Quartile values	1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8	All
Minimum	0	0	0	-109	-109	-73	-116	-201	-45	-81	-131	-118	-95	-77	-26	27	-201
1st Quartile	0	0	0	0	0	0	2	-30	62	112	39	104	84	86	192	181	36
Median	485	403	578	639	598	263	699	595	552	732	668	507	818	751	934	1,053	587
Average	478	440	581	566	563	316	611	579	519	721	700	519	848	802	886	1,048	636
2nd Quartile	708	674	923	864	974	597	987	875	817	1,101	1,160	794	1,424	1,290	1,470	1,788	998
Maximum	1,438	1,363	1,662	1,658	1,690	1,171	1,830	1,908	1,362	1,913	2,021	1,343	2,177	2,105	1,932	2,129	2,177

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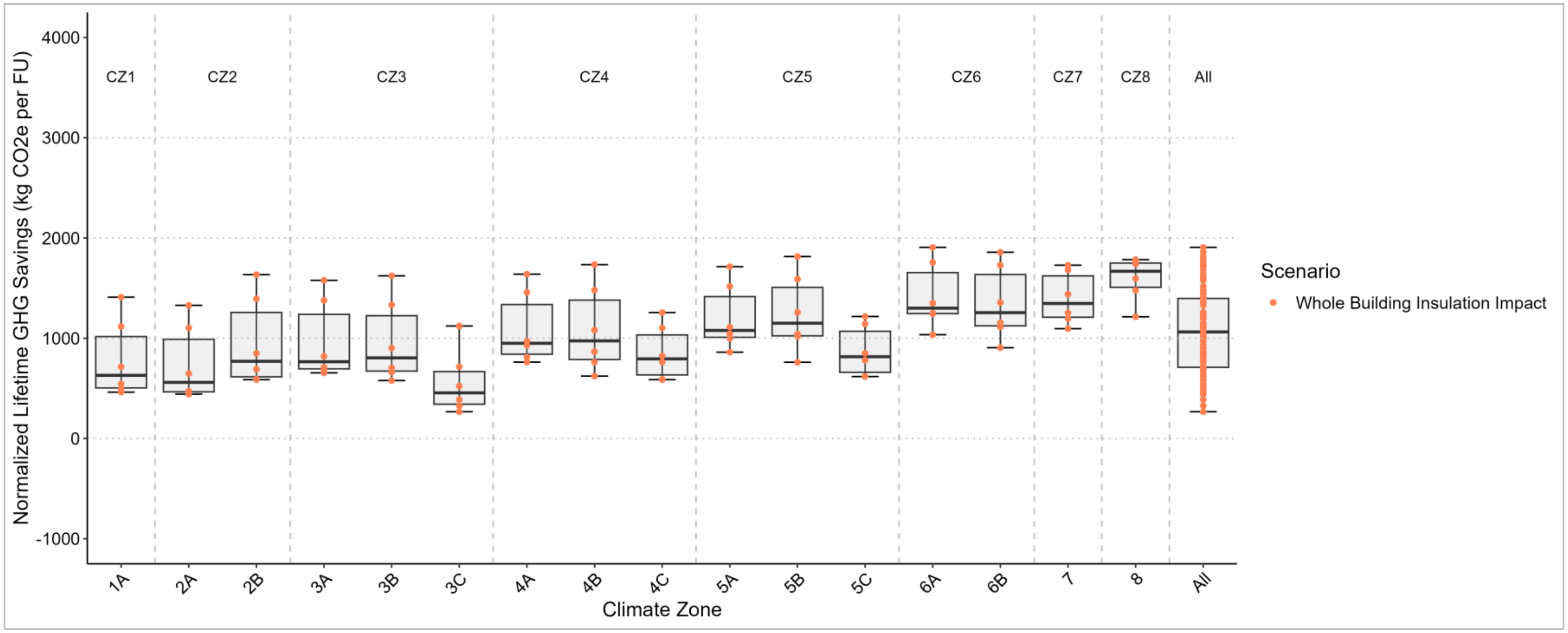

Figure 6: Distribution of Normalized Lifetime GHG Savings per Unit Functional Unit of Insulation in Whole Building (Commercial Prototypes – Scenario 1)

Table 18: Summary of Key Values for Normalized Lifetime GHG Savings per Functional Unit in Whole Building (Commercial Prototypes – Scenario 1)

Quartile values	1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8	All
Minimum	462	443	587	655	578	267	762	623	587	861	761	618	1,035	905	1,096	1,214	267
Quartile 01	484	458	590	681	640	312	799	727	590	963	954	620	1,192	1,061	1,170	1,412	708
Median	630	560	770	766	804	455	950	974	794	1,078	1,150	816	1,300	1,255	1,347	1,668	1,063
Average	790	743	958	972	967	557	1,095	1,091	854	1,208	1,247	872	1,424	1,353	1,399	1,594	1,070
Quartile 02	1,190	1,160	1,453	1,427	1,405	817	1,504	1,544	1,141	1,566	1,646	1,161	1,794	1,761	1,695	1,761	1,406
Maximum	1,410	1,328	1,634	1,577	1,623	1,122	1,639	1,735	1,256	1,714	1,815	1,217	1,906	1,858	1,729	1,784	1,906

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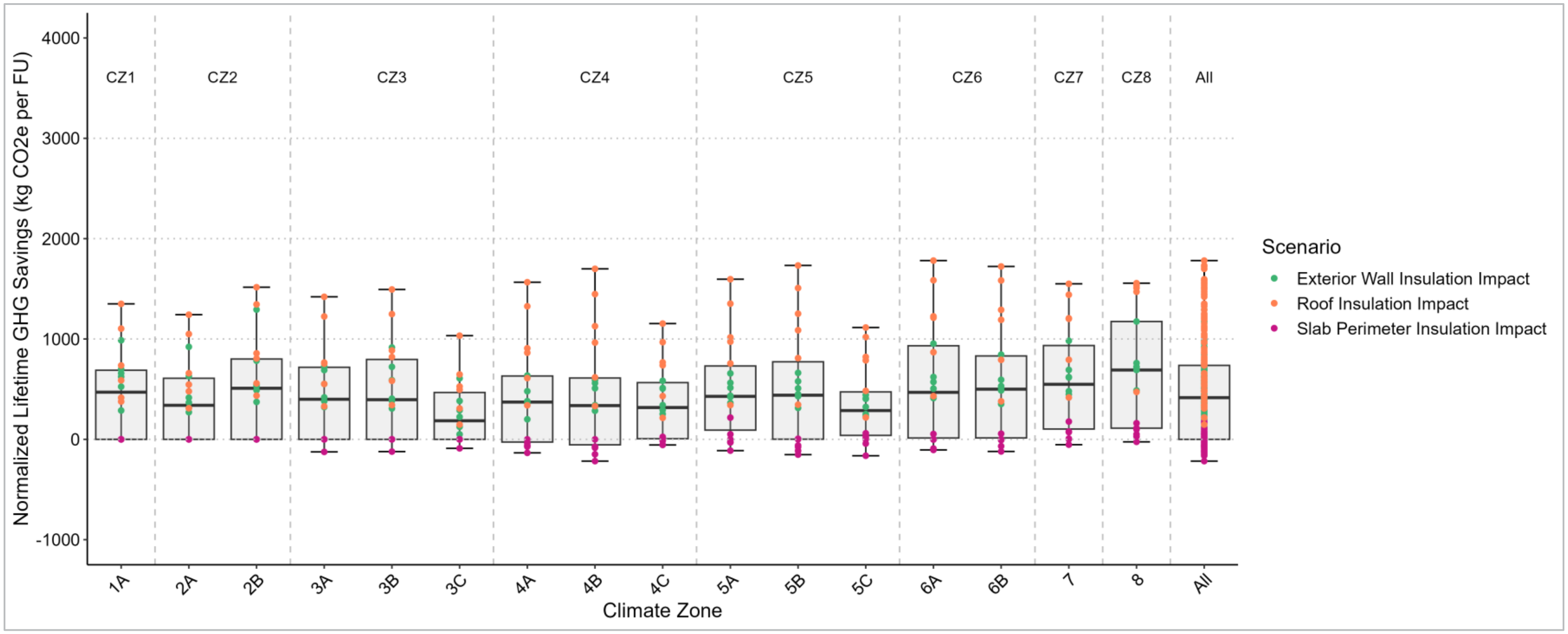

Figure 7: Distribution of Normalized Lifetime GHG Savings per Functional Unit of Insulation in Individual Envelope Elements (Commercial Prototypes – Scenario 2)

Table 19: Summary of Key Values for Normalized Lifetime GHG Savings per Functional Unit in Individual Envelope Elements (Commercial Prototypes – Scenario 2)

Quartile values	1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8	All
Minimum	0	0	0	-125	-122	-90	-135	-217	-56	-113	-152	-163	-106	-121	-53	-25	-217
1st Quartile	0	0	0	0	0	0	-42	-73	-1	38	-15	28	0	0	76	108	0
Median	470	339	509	399	395	185	371	336	317	428	440	287	468	500	548	706	416
Average	464	400	530	445	476	264	440	456	370	505	516	356	580	563	596	700	479
2nd Quartile	708	637	819	734	837	503	693	704	622	810	879	559	1,019	931	1,037	1,248	750
Maximum	1,350	1,242	1,516	1,421	1,494	1,033	1,566	1,699	1,154	1,596	1,733	1,114	1,781	1,723	1,550	1,556	1,781

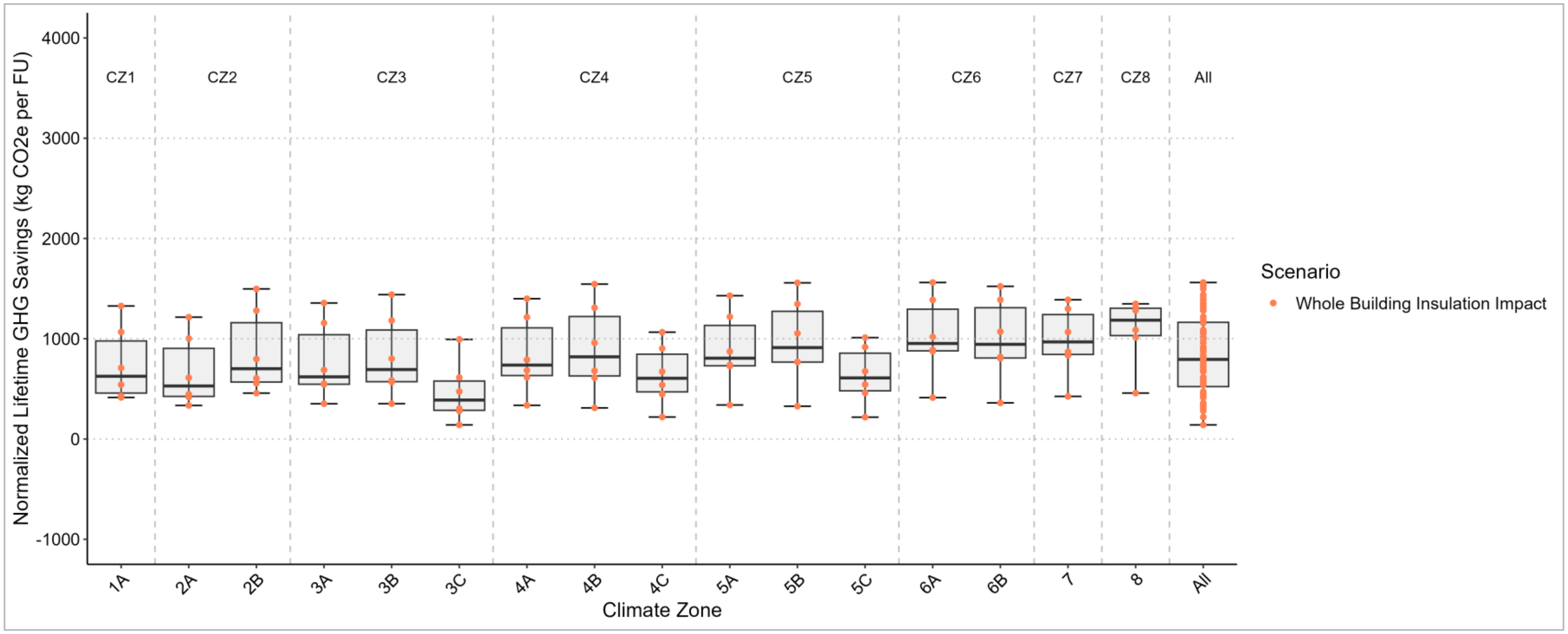

Figure 8: Distribution of Normalized Lifetime GHG Savings per Unit Functional Unit of Insulation in Whole Building (Commercial Prototypes – Scenario 2)

Table 20: Summary of Key Values for Normalized Lifetime GHG Savings per Functional Unit in Whole Building (Commercial Prototypes – Scenario 2)

Quartile values	1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8	All
Minimum	415	335	458	352	353	141	336	310	219	340	327	218	413	360	425	459	141
Quartile 01	427	397	531	497	514	246	546	537	390	630	657	399	760	694	732	874	490
Median	626	529	701	620	693	389	737	820	606	806	912	609	953	944	968	1,185	794
Average	749	671	866	775	821	468	840	903	641	888	970	637	1,024	994	981	1,084	832
Quartile 02	1,132	1,055	1,335	1,207	1,247	709	1,261	1,368	944	1,272	1,399	940	1,431	1,422	1,322	1,321	1,176
Maximum	1,327	1,215	1,497	1,357	1,440	994	1,399	1,545	1,066	1,429	1,558	1,011	1,561	1,523	1,389	1,348	1,561

5 Conclusions

The key takeaways from this study can be summarized as follows:

Thermal insulation on the building envelope is the first and most significant line of defense against heat exchange between the indoors and the outdoors. Building envelope insulation is critical to the design and sizing of other elements such as HVAC equipment. The distribution of normalized GHG savings in all climate zones demonstrates a positive impact of insulation on GHG emission reduction. This is primarily because of the significant effect of building envelope insulation on the heating and cooling demand of the living spaces. Buildings in colder climates were observed to have the highest average and median lifetime energy and carbon savings, highlighting the significant impact of envelope insulation on reducing the heating load during winter.

The scenario involving the full transition into heat pump heating systems showed a drop in the normalized GHG savings per functional unit of insulation relative to the scenario with existing heating systems. This is primarily due to the improved efficiency of the heat pump relative to natural gas and fuel oil systems, resulting in lower annual energy consumptions.

The results for the commercial prototypes were similar to those for the residential. However, the commercial prototypes generally exhibited higher normalized emission savings per functional unit of insulation. This indicates that the thermal insulation in commercial building envelopes has stronger impact on energy consumption reduction, yielding more GHG savings per unit of thermal insulation.

For the residential single-family home prototype, assuming a uniform distribution of existing heating systems, the median lifetime carbon savings were found to be 434 kg CO_2e/FU. The value ranged from 197 kg CO_2e/FU for cooling dominant climates to 861 kg CO_2e/FU for heating dominant climates. Assuming a future transition of the heating system into heat pumps, the median lifetime carbon savings were found to be 332 kg CO_2e/FU. The value ranged from 160 kg CO_2e/FU for cooling dominant climates to 1,128 kg CO_2e/FU for heating dominant climates.

For the commercial prototypes with natural gas heating systems, the median lifetime carbon savings were found to be 1,063 kg CO_2e/FU. The value ranged from 630 kg CO_2e/FU for cooling dominant climates to 1,668 kg CO_2e/FU for heating dominant climates. Assuming a future transition of the heating system into heat pumps, the median lifetime carbon savings were found to be 794 kg CO_2e/FU. The value ranged from 626 kg CO_2e/FU for cooling dominant climates to 1,185 kg CO_2e/FU for heating dominant climates.

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Appendix A

Building enevlope R-values utilized in the building simulations across climate zones are described below.

Residential Prototypes

A. Above-Grade Exterior Wall

Table A. 1 shows the R-values used in the study for exterior wall across the eight climate zones. The left column lists the construction layers employed in the prototypical building EnergyPlus models. The highlighted elements are the insulation layers with their varying R-values depending on the climate zone and the respective IECC 2021 requirements.

Table A. 1: R-Values for Above-Grade Exterior Wall

Construction Layer	R-value (ft^2.F.h/Btu)								
	Baseline	IECC 2021 Insulation Level							
	-	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
syn_stucco	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
sheathing_consol_layer	**0.00**	**0.77**	**0.77**	**0.77**	**5.04**	**5.04**	**5.04**	**5.04**	**5.04**
OSB_7/16in	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
wall_consol_layer	**1.24**	**8.71**	**8.71**	**13.69**	**13.69**	**13.69**	**13.69**	**13.69**	**13.69**
Drywall_1/2in	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Assembly R-Value	**2.43**	**10.67**	**10.67**	**15.64**	**19.62**	**19.62**	**19.62**	**19.62**	**19.62**

B. Crawlspace Wall

Table A. 2 shows the R-values used in the study for crawlspace wall across the eight climate zones.

Table A. 2: R-Values for Crawlspace Wall

Construction Layer	R-value (ft^2.F.h/Btu)								
	Baseline	IECC 2021 Insulation Level							
	-	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
Exterior insulation	**0.00**	**0.00**	**0.00**	**5.00**	**10.00**	**15.00**	**15.00**	**15.00**	**15.00**
4" concrete wall	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Assembly R-Value	**0.44**	**0.44**	**0.44**	**5.44**	**10.44**	**15.44**	**15.44**	**15.44**	**15.44**

C. Basement Wall

Table A. 3 shows the R-values used in the study for basement wall across the eight climate zones.

Table A. 3: R-Values for Basement Wall

Construction Layer	R-value (ft^2.F.h/Btu)								
	Baseline	IECC 2021 Insulation Level							
	-	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
Exterior Insulation	**0.00**	**0.00**	**0.00**	**5.00**	**10.00**	**15.00**	**15.00**	**15.00**	**15.00**

8" Concrete Wall	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Drywall_1/2in	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Assembly R-Value	**1.60**	**1.60**	**1.60**	**6.60**	**11.60**	**16.60**	**16.60**	**16.60**	**16.60**

D. Crawlspace and Unheated Basement Ceiling

Table A. 4 shows the R-values used in the study for crawlspace and unheated basement ceiling across the eight climate zones.

Table A. 4: R-values for Crawlspace and Unheated Basement Ceiling

Construction Layer	R-value (ft².F.h/Btu)								
	Baseline	IECC 2021 Insulation Level							
	-	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
floor_consol_layer	**1.82**	**10.97**	**10.97**	**16.19**	**16.19**	**25.65**	**25.65**	**32.46**	**32.46**
Plywood_3/4in	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
Carpet and Pad	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40
Assembly R-Value	**5.16**	**14.32**	**14.32**	**19.54**	**19.54**	**29.00**	**29.00**	**35.80**	**35.80**

E. Slab

Table A. 5 shows the R-values used in the study for slab across the eight climate zones.

Table A. 5: R-values Slab Perimeter Insulation

Construction Layer	R-value (ft².F.h/Btu)								
	Baseline	IECC 2021 Insulation Level							
	-	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
Slab perimeter insulation	**0.00**	**0.00**	**0.00**	**10.00**	**10.00**	**10.00**	**10.00**	**10.00**	**10.00**
Assembly R-Value	0.00	0.00	0.00	10.00	10.00	10.00	10.00	10.00	10.00

F. Attic Floor

Table A. 6 shows the R-values used in the study for attic floor across the eight climate zones.

Table A. 6: R-Values for Attic Floor

Construction Layer	R-value (ft².F.h/Btu)								
	Baseline	IECC 2021 Insulation Level							
	-	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
ceil_consol_layer	**1.08**	**26.08**	**36.35**	**40.70**	**40.70**	**40.70**	**40.70**	**40.70**	**40.70**
Drywall_1/2in	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Assembly R-Value	**1.53**	**26.53**	**37.10**	**41.16**	**41.16**	**41.16**	**41.16**	**41.16**	**41.16**

Commercial Prototypes

A. Above-Grade Non-Residential Exterior Wall

Table A. 7 shows the R-values used in the study for non-residential above grade exterior wall across the eight climate zones.

Table A. 7: R-Values for Non-Residential Above-Grade Exterior Wall

Construction Layer	R-value (ft².F.h/Btu)								
	Baseline	ASHRAE 90.1 – 2019 Insulation Level							
	-	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
F07 25mm stucco	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
G01 16mm gypsum board	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Nonres_Exterior_Wall_ Insulation	**0.10**	**5.89**	**9.73**	**10.81**	**13.45**	**16.00**	**18.23**	**18.23**	**24.85**
G01 16mm gypsum board	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Assembly R-Value	**1.43**	**7.22**	**11.06**	**12.13**	**14.77**	**17.33**	**19.56**	**19.56**	**26.18**

B. Above-Grade Residential Exterior Wall

Table A. 8 shows the R-values used in the study for residential above grade exterior wall across the eight climate zones.

Table A. 8: R-Values for Residential Above-Grade Exterior Wall

Construction Layer	R-value (ft².F.h/Btu)								
	Baseline	ASHRAE 90.1 – 2019 Insulation Level							
	-	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
F07 25mm stucco	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
G01 16mm gypsum board	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Res_Exterior_Wall_ Insulation	**0.10**	**5.89**	**13.45**	**13.45**	**13.45**	**16.00**	**18.23**	**21.63**	**24.85**
G01 16mm gypsum board	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Assembly R-Value	**1.43**	**7.22**	**14.77**	**14.77**	**14.77**	**17.33**	**19.56**	**22.96**	**26.18**

C. Above-Grade Non-Residential Exterior Wall for Warehouse Buildings

Table A. 9 shows the R-values used in the study for non-residential exterior wall across the eight climate zones.

Table A. 9: R-Values for Non-Residential Above-Grade Exterior Wall for Warehouse Buildings

Construction Layer	R-value (ft².F.h/Btu)								
	Baseline	ASHRAE 90.1 – 2019 Insulation Level							
	-	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
F0 25mm Metal surface	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20
Non Res_Exterior_Wall_ Insulation	**0.00**	**9.33**	**9.33**	**9.33**	**15.36**	**18.70**	**18.70**	**21.42**	**24.34**
G01 16mm gypsum board	0.00	0.56	0.56	0.56	0.56	0.56	0.56	0.56	24.85
Assembly R-Value	**0.00**	**9.90**	**9.90**	**9.90**	**15.93**	**19.26**	**19.26**	**21.99**	**24.91**

D. Above-Grade Exterior Wall of Semi-Heated Spaces

Table A. 10 shows the R-values used in the study for semi-heated exterior wall across the eight climate zones.

Table A. 10: R-Values for Above-Grade Exterior Wall of Semi-Heated Spaces

Construction Layer	R-value (ft²·F·h/Btu)								
	Baseline	ASHRAE 90.1 – 2019 Insulation Level							
	-	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
F0 25mm Metal surface	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Semiheated_Exterior_Wall_ Insulation	**0.00**	**1.54**	**4.87**	**4.87**	**4.87**	**9.33**	**9.33**	**12.59**	**15.36**
G01 16mm gypsum board	0.00	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Assembly R-Value	**0.00**	**2.10**	**5.44**	**5.44**	**5.44**	**9.90**	**9.90**	**13.15**	**15.93**

E. Non-Residential Roof

Table A. 11 shows the R-values used in the study for non-residential roof across the eight climate zones.

Table A. 11: R-Values for Non-Residential Roof

Construction Layer	R-value (ft²·F·h/Btu)								
	Baseline	ASHRAE 90.1 – 2019 Insulation Level							
	-	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
F13 Built-up roofing	0.00	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
Nonres_Roof_Insulation	**0.00**	**19.71**	**24.52**	**24.52**	**30.13**	**30.13**	**30.13**	**34.60**	**34.60**
F08 Metal surface	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Assembly R-Value	**0.00**	**20.05**	**24.86**	**24.86**	**30.47**	**30.47**	**30.47**	**34.93**	**34.93**

F. Residential Roof

Table A. 12 shows the R-values used in the study for residential roof across the eight climate zones.

Table A. 12: R-Values for Residential Roof

Construction Layer	R-value (ft²·F·h/Btu)								
	Baseline	ASHRAE 90.1 – 2019 Insulation Level							
	-	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
F13 Built-up roofing	0.00	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
Res_Roof_Insulation	**0.00**	**24.47**	**24.47**	**24.47**	**30.13**	**30.13**	**30.13**	**34.60**	**34.60**
F08 Metal surface	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Assembly R-Value	**0.00**	**24.81**	**24.81**	**24.81**	**30.47**	**30.47**	**30.47**	**34.93**	**34.93**

G. Non-Residential Roof

Table A. 13 shows the R-values used in the study for non-residential roof of warehouse buildings across the eight climate zones.

Table A. 13: R-Values for Non-Residential Roof for Warehouse Buildings

Construction Layer	R-value (ft².F.h/Btu)								
	Baseline	ASHRAE 90.1 – 2019 Insulation Level							
	-	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
F08 Metal surface	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nonres_Roof_Insulation	**0.00**	**23.61**	**23.61**	**23.61**	**26.24**	**26.24**	**31.48**	**33.68**	**37.68**
Assembly R-Value	**0.00**	**23.61**	**23.61**	**23.61**	**26.24**	**26.24**	**31.48**	**33.68**	**37.68**

H. Semi-Heated Roof

Table A. 14 shows the R-values used in the study for roof of semi-heated spaces across the eight climate zones.

Table A. 14: R-Values for Roof of Semi-Heated Spaces

Construction Layer	R-value (ft².F.h/Btu)								
	Baseline	ASHRAE 90.1 – 2019 Insulation Level							
	-	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
F08 Metal surface	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Semiheated_Roof_ Insulation	**0.00**	**7.92**	**9.64**	**9.64**	**11.41**	**11.41**	**15.89**	**26.24**	**26.24**
Assembly R-Value	**0.00**	**7.92**	**9.64**	**9.64**	**11.41**	**11.41**	**15.89**	**26.24**	**26.24**

I. Non-Residential Slab

Table A. 15 shows the R-values used in the study for non-residential slab across the eight climate zones.

Table A. 15: R-Values for Non-Residential Slab Perimeter

Construction Layer	F-factor (Btu/h.ft.°F)								
	Baseline	ASHRAE 90.1 – 2019 Insulation Level							
	-	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
Slab perimeter insulation	0.73	0.73	0.73	0.73	0.52	0.52	0.51	0.51	0.43
Assembly R-Value	**0.73**	**0.73**	**0.73**	**0.73**	**0.52**	**0.52**	**0.51**	**0.51**	**0.43**

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J. Residential Slab

Table A. 16 shows the R-values used in the study for residential slab across the eight climate zones.

Table A. 16: R-Values for Residential Slab Perimeter

Construction Layer	F-factor (Btu/h.ft.°F)								
	Baseline	ASHRAE 90.1 – 2019 Insulation Level							
	-	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
Slab perimeter insulation	0.73	0.73	0.73	0.54	0.52	0.51	0.43	0.43	0.42
Assembly R-Value	**0.73**	**0.73**	**0.73**	**0.54**	**0.52**	**0.51**	**0.43**	**0.43**	**0.42**

K. Semi-Heated Slab

Table A. 17 shows the R-values used in the study for semiheated slab across the eight climate zones.

Table A. 17: R-Values for Semi-Heated Slab Perimeter

Construction Layer	F-factor (Btu/h.ft.°F)								
	Baseline	ASHRAE 90.1 – 2019 Insulation Level							
	-	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
Slab perimeter insulation	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.54
Assembly R-Value	**0.73**	**0.73**	**0.73**	**0.73**	**0.73**	**0.73**	**0.73**	**0.73**	**0.54**

Appendix B

List of analysis workbooks attached in the deliverable section are as follows:

R Calculation_Residential.xlsx	This workbook contains the residential R value calculation for each building paramter across all climate zones.
R Calculation_Commercial.xlsx	This workbook contains the commercial R value calculation for each building paramter across all climate zones.
Carbon emission calculation_Residential.xlsx	This workbook contains the calculation of carbon emissions per functional unit for residential scenario 01 (Current Heating Systems Mix)
Electrification Carbon emission calculation_Residential.xlsx	This workbook contains the calculation of carbon emissions per functional unit for residential scenario 02 (100% Heat Pump Systems)
Carbon emission calculation_Commercial.xlsx	This workbook contains the calculation of carbon emissions per functional unit for commercial scenario 01 (Current Heating Systems Mix)
Electrification Carbon emission calculation_Commercial.xlsx	This workbook contains the calculation of carbon emissions per functional unit for commercial scenario 02 (100% Heat Pump Systems)