Determination of Total Carbon Impact of Plastic Insulation Materials

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August 29, 2023

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Executive Summary

ICF carried out an energy and carbon modeling study to evaluate the life-cycle energy and green house gas (GHG) savings attributable to the application of plastic insulation materials for both residential and commercial building envelopes. The study involved a wide range of plastic insulation materials, including extruded polystyrene (XPS), expanded polystyrene (EPS), closed-cell spray polyurethane foam (cc-SPF), open-cell spray polyurethane foam (oc-SPF) and polyisocyanurate (Polyiso). Two building prototypes were considered, representative of the predominant building types in the residential and commercial sectors: a single-family detached home with a heated basement and a medium office building with an unheated slab on grade. The prototypical energy models developed by Pacific Northwest National Laboratory (PNNL) for code-compliant buildings were utilized in this study. Two climate zones were selected to explore the energy and carbon impact of using the plastic insulation materials in temperate (CZ3) as well as cold (CZ5) climates. The energy and carbon savings due to the application of insulation materials to the three key components of the building envelope (walls, roof and foundation) were evaluated. To better understand the carbon return on investment of the insulation materials, two metrics were reported: (1) the carbon payback period, defined as the time required for the annual carbon savings to break even with the embodied carbon in the insulation materials, and (2) the carbon avoidance ratio, defined as the ratio of lifetime carbon savings to the embodied carbon in the insulation materials.

A total of 24 models that span six different climate zones (PNNL provides building model in three moisture regimes - CZ3A, CZ3B, CZ3C, CZ5A, CZ5B, CZ5C) and four different heating systems were simulated for the residential analysis. These heating systems are: electric resistance furnace, natural gas furnace, fuel oil furnace and electric air-source heat pump. For the commercial medium office prototype, a total of 6 models that span six different climate zones were simulated since only one heating system type (a natural-gas fired packaged system with electric resistance terminal reheat coils) was assumed in all PNNL medium office building models. Typical meteorological year (i.e., TMY) weather data was obtained for the six representative weather locations.

This study investigated the following scenarios:

Residential Prototype – Single-family Detached Home

- R0 – No Insulation: this scenario models the home exterior envelope with no insulation
- R1 – Basement + Attic Insulation: this scenario models the home with basement and attic insulation but with no insulation on the exterior above-grade walls.
- R2 – Wall + Attic Insulation: this scenario models the home with exterior wall and attic insulation but with no insulation on the basement walls.
- R3 – Wall + Basement Insulation: this scenario models the home with exterior wall and basement insulation but with a vented uninsulated attic.
- R4 – Fully Insulated Home: this scenario models a home with an entirely insulated envelope.

Commercial Prototype – Medium Office Building

- C0 – No Insulation: this scenario models the office envelope with no insulation.

- C1 – Roof + Slab Insulation: this scenario models the office with roof and slab perimeter insulation but with no insulation on the exterior above-grade walls.
- C2 – Wall + Roof Insulation: this scenario models the office with exterior wall and roof insulation but with no insulation on the slab perimeter.
- C3 – Wall + Slab Insulation: this scenario models the office with exterior wall and slab perimeter insulation but with no roof insulation.
- C4 – Fully Insulated Office: this scenario models the office with an entirely insulated envelope.

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

ACC provided representative values of the embodied carbon in the insulation materials of interest. Then, the total embodied carbon in each of the scenarios above was calculated using derived information on the type and volume of insulation materials used.

A total of 120 simulations were performed for the residential prototype and 27 simulations were performed for the commercial prototype. 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 applying weighting factors representative of the distribution of single-family detached homes with different heating systems and in different climate zones. Similarly, the results for the commercial prototype in different climate zones were averaged 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 emission rates for the state of Georgia were chosen as a conservative representation of emissions from the electricity generation in climate zones 3 and 5. 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 main focus of the study was to evaluate the lifecycle (defined herein as 75 years) carbon impacts due to the application of the plastic insulation materials to the prototypical building envelopes. For this reason, two metrics were developed: the carbon payback period and the carbon avoidance ratio. The carbon payback period was calculated as the period required for the cumulative GHG savings to break even with the embodied carbon. The carbon avoidance ratio was defined as the ratio of the lifetime GHG savings to the embodied carbon.

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

- Scenario 1: A scenario that assumes that the current distribution of heating systems prevails 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 takeaways from this study can be summarized as follows:

Residential Prototype: Single-family Detached Home

The insulation presented a larger impact on heating and cooling end uses. Wall insulation showed the largest impact on the savings, followed by the attic insulation, then the basement wall insulation. This was because the surface area of exterior above-grade wall is 1.5 times that of the attic exterior boundary. The basement wall insulation exhibited the smallest impact likely due to the inherent insulation characteristics of the soil surrounding the exterior surface of the basement wall. The savings in CZ5 are multiple times larger than that in CZ3 likely due to the dominance of space heating energy consumption in CZ5. Switching to 100% heat pump systems, the amount of energy savings due to the electrification of the heating system is greatly dependant on the efficiency of the replaced system. For example, this study showed larger savings in CZ5 compared to CZ3 due to the higher penetration of heat pumps currently in CZ3 (~70% of homes) compared to CZ5 (~21% of homes).

For both scenarios, the carbon payback period was found to be under a year for all simulated cases. Shorter payback periods were observed in CZ5, despite the higher embodied carbon, due to the much larger first year GHG savings relative to CZ3. This highlights the critical role of insulation in heating dominant regions. The carbon avoidance ratio for the whole home insulation case was found in the range of 30-171 for CZ3 (i.e., “spending” 1 unit of carbon to save 30-171 times the carbon) and 60-348 for CZ5, depending on the heating system scenario and the future predictions of emission rates from electricity generation. This highlights the fact that the GHG emission savings over the lifetime of the investigated plastic insulation are one to two orders of magnitude higher than the embodied carbon.

Commercial Prototype: Medium Office Building

Roof insulation has the largest impact on the savings, followed by the exterior wall insulation, then the slab perimeter insulation. This was because the surface area of roof is 1.25 times that of the exterior above-grade wall. The impact of the slab perimeter insulation was shown to be insignificant, likely due to the dominant effect of the exterior walls on the ground floor in addition to the inherent insulation characteristics of the soil surrounding the slab perimeter. One interesting observation on cooling electricity consumption and savings in CZ5 was that the scenarios with partial insulation showed lower consumption and larger savings than the scenario of full building insulation. Also, the scenario with no roof insulation exhibited larger cooling consumption than the scenario with no insulation, indicating negative savings in cooling electricity use. Such behaviors are likely attributed to the effect of insulation on reducing the free cooling imparted by the cooler outdoor temperatures during summer in CZ5. Scenario 2 showed that the average office generally exhibits lower electricity consumption due to the transition to 100% heat pump systems.

Similar to the residential prototype, the carbon payback period for all insulation scenarios in the commercial prototype was found to be in the range of 7.5 – 13 months for CZ3, and 4.4 – 7.7 months for CZ5. The carbon avoidance ratio for the case with whole office insulation ranged between 18-208 for CZ3 and 29-305 for CZ5, depending on the heating system scenario and the future predictions of emission rates from electricity generation.

1 Introduction

ICF was tasked by the American Chemistry Council (ACC) to evaluate the life-cycle energy and GHG savings attributable to the application of plastic insulation materials for both residential and commercial building envelopes. ACC was interested in a wide range of plastic insulation materials, including extruded polystyrene (XPS), expanded polystyrene (EPS), closed-cell spray polyurethane foam (cc-SPF), open-cell spray polyurethane foam (oc-SPF) and polyisocyanurate (Polyiso). ACC selected two prototypes representative of the predominant building types in the residential and commercial sectors: single-family detached home for residential and medium office for commercial. Two climate zones were selected to explore the energy and carbon impact of using the plastic insulation materials in temperate (CZ3) as well as cold (CZ5) climates.

This report presents the modeling and analysis framework used to evaluate the energy and GHG savings from the application of plastic insulation materials to the key components of the building envelope: roof, walls and foundation. In addition, this study reports the embodied carbon in the manufacturing and application processes of the latest generation of insulation materials available in today's market, and provides an estimate of the carbon payback period as well as the ratio of embodied carbon to lifetime savings.

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

To estimate the energy impacts of different types of plastic insulation, ICF utilized the national prototypical building models developed by Pacific Nothwest 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 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 8 different climate zones of the United States.

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

The study analyzed two prototype buildings, a single-family detached home and a medium office building, across two climate zones, tempatrate (CZ3) and cold (CZ5). 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 in three moisture regimes, i.e., A: Moist, B: Dry, and C: Marine. As such, we downloaded and updated a total of 24 models that span the six different climate zones (i..e, CZ3A, CZ3B, CZ3C and CZ5A, CZ5B, CZ5C) and four different heating system types. The models reflecting the latest code level update (i.e., IECC 2021) were used. For the commercial medium office prototype, PNNL provides only one representative model per building type for each of the six climate zones, as different HVAC systems are not explored. As such, we downloaded a total of 6 models reflecting the latest code level update (i.e., ASHRAE 90.1 - 2019).

The PNNL models incorporate several changes introduced by the 2013 edition of ASHRAE Standard 169, Climatic Data for Building Design Standards (ASHRAE 2013). ASHRAE 169-2013 redefined climate zones and moisture regimes based on a more recent period of weather data. Table 1 presents the list of representative cities and corrsponding weather station locations for the climate zones of interest to the current study.

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}
CZ3A	Atlanta, Georgia	Atlanta/Hartsfield Jackson International Airport, Georgia	2,498	2,099
CZ3B	El Paso, Texas	El Paso International Airport, Texas	2,012	2,972
CZ3C	San Diego, California	San Diego/Brown Field Municipal Airport, California	1,377	763
CZ5A	Buffalo, New York	Buffalo Niagara International Airport, New York	6,242	769
CZ5B	Denver, Colorado	Denver/Aurora/Buckley AFB, Colorado	5,737	832
CZ5C	Port Angeles, Washington	Port Angeles/William R Fairchild International Airport, Washington	5,488	20

ICF proposed to use the most updated weather files for the top climate zones to reflect the recent changes to the weather conditions. As such, we downloaded the TMYx files for the six representative weather locations[2]. The TMYx files are typical meterological data derived from hourly weather data from the most recent 15 years (2007-2021) in the ISD (US NOAA's Integrated Surface Database) using the TMY/ISO 15927-4:2005 methodologies.

EnergyPlus models require a detailed breakdown of the construction layers of each different envelope component (i.e., the exterior wall, the roof and the basement or slab) to simulate the

[2] https://climate.onebuilding.org/

heat exchange between the indoor space and the outdoors. In order to capture the accurate thermal characteristics of the plastic insulation materials, ICF conducted online research to identify representative thermo-physical properties of these materials. Table 2 lists the thermo-physical properties of the plastic insulation materials used in this study. The R-values of products in the market may vary slightly.

Table 2: Representative Thermo-physical Properties of Plastic Insulation Materials

Insulation Material	R-value per inch thickness	Thermal Conductivity, Btu/h-ft-°F (W/m.K)	Density, lb/ft^3 (kg/m^3)	Specific Heat, Btu/lb.°F (J/kg.K)
XPS	5.00	0.01667 (0.02885)	1.56 (25)	0.36 (1500)
EPS	4.00	0.02083 (0.03606)	1.56 (25)	0.36 (1500)
cc-SPF	6.50	0.01282 (0.02219)	2.18 (35)	0.35 (1450)
oc-SPF	3.50	0.02381 (0.04121)	2.18 (35)	0.35 (1450)
Polyiso	5.80	0.01437 (0.02487)	1.56 (25)	0.36 (1500)

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

The prototypical building characteristics for the single-family detached home are as follows:

Building Size: 2-story home with a conditioned area of 3,565 ft^2. This includes 2,377 ft^2 of above grade living space and 1,188 ft^2 of conditioned basement space.

Foundation Type: Heated Basement

HVAC Systems:

- Air Conditioning: DX Cooling Coil with rated COP = 4.0. The air conditoning performance metrics developed by PNNL were not altered, as it was assumed that they conform with the Federal minimum standards.
- Heating: 4 Systems
  - Electric Resistance
  - Gas Furnace (80% Efficiency)
  - Oil Furnace (78% Efficiency)
  - Heat Pump (with back-up electric resistance heating). The heat pump performance metrics developed by PNNL were used, to conform with the Federal minimum standards.

ACC was interested in exploring the impact of the following five scenarios, shown in Table 3, on the energy and GHG emissions over 75-year lifetime of the plastic insulation materials. These scenarios where selected to allow the effect of insulation in each building envelope assembly to be assessed by evaluating the modeling results relative to scenarios R0 (uninsulated home) and R4 (fully insulated home). Note that "R" in the scenario label stands for "Residential", and it should not be confused for the R-value of the insulation material. Throughout this report, the R-value of the insulation will be hyphened to distinguish it from the simulated scenarios for the residential prototype. The 75-year lifetime was selected as it is consistent with the UL Product Category Rule for Building Envelope Thermal Insulation EPD Requirements.

Table 3: Simulated Scenarios for Residential Prototype

Scenario	Description
R0	No Insulation
R1	Basement + Attic Insulation (No Wall Insulation)
R2	Wall + Attic Insulation (No Basement insulation)
R3	Wall + Basement Insulation (No Attic Insulation)
R4	Fully Insulated Home (Whole Home Insulation)

Table 4 shows the minimum prescripitve insulation R-values required by IECC 2021 code for the different envelope components in climate zones 3 and 5. Upon consultation with ACC and reviewing common practices in home insulation, Table 4 shows the selected insulation materials assumed for each component. In some cases a "blended" insulation component was used to represent the different plastic insulation material choices commonly used for a particular building envelope assembly.

Table 4: IECC 2021 Minimum Insulation R-Values for Different Envelope Components in Climate Zones 3 and 5

Location	Climate Zone	
	CZ 3	CZ 5
Above-Grade Exterior Wall Insulation	R-13 oc-SPF/cc-SPF blend 50/50 in cavity, R-5 continuous insulation (ci) XPS/EPS foam sheathing blend 50/50	R-13 oc-SPF/cc-SPF blend 50/50 in cavity, R-10ci XPS/EPS foam sheathing blend 50/50
Basement Exterior Wall Insulation	R-5ci exterior XPS	R-10ci exterior XPS, R-5ci interior XPS/EPS foam sheathing blend 50/50
Unvented Attic Insulation (Roof and Gable End Wall)		
Roof Insulation	R-38 cc-SPF, as allowed by R402.2.1, assuming that insulation is applied to full R-value and over the top plate at the eaves.	R-49 cc-SPF, as allowed by R402.2.1, assuming that insulation is applied to full R-value and over the top plate at the eaves
Gable End Wall Insulation	R-13 oc-SPF/cc-SPF blend 50/50 in cavity, R-5ci XPS/EPS foam sheathing blend 50/50	R-13 oc-SPF/cc-SPF blend 50/50 in cavity, R-10ci XPS/EPS foam sheathing blend 50/50

The prototypical building models were reviewed and adapted to ensure the conformance of the envelope compoments' construction with the IECC 2021 code requirements. The following section details the breakdown of the construction layers of the envelope components.

A. Above-Grade Exterior Wall

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%[3]. Then, two parallel heat flow paths were developed to calculate the insulation effective R-value that is used in the EnergyPlus models. Table 5 shows the construction layers of the exterior wall and their R-values along the studs path and the cavity path. The construction layers are divided into two groups: the structural and finish layers (e.g., wood studs, drywall and stucco) and the insulation layers (shown in bold in the table). It is worth noting here that the depth of the studs is assumed to be 3.5”. The spray foam is assumed to fill the cavity up to a thickness corresponding to the target R-value. In the case when the calculated thickness of the foam insulation was smaller than the depth of the cavity, the remainder of the cavity was assumed to be filled with air. In the case when the calculated thickness was greater than the depth of the cavity, an extra layer of continuous foam insulation was assumed to extend beyond the studs section.

Table 5: R-Values of Construction Layers of Exterior Wall through Studs Path and Cavity Path (Starting from the Outer Layer)

Construction Layer	CZ3		CZ5	
	Studs Path	Cavity Path	Studs Path	Cavity Path
syn_stucco	0.20	0.20	0.20	0.20
sheathing_consol_layer (50/50 XPS/EPS)	**5.00**	**5.00**	**10.00**	**10.00**
OSB_7/16in	0.54	0.54	0.54	0.54
wood studs	4.38		4.38	
wall_consol_layer (50/50 oc-SPF/cc-SPF)		**13.00**		**13.00**
air cavity_1in		0.26		0.26
drywall_1/2in	0.45	0.45	0.45	0.45
Total R-value	10.57	19.45	15.57	24.45

The total R-values for the stud and cavity paths shown in Table 5 were then utilized to calculate the total R-value of the assembly, which was found to be 16.08 and 21.40 for climate zones 3 and 5, respectively[4]. One limitation of the EnergyPlus software is that it cannot model an assembly comprising parallel paths of heat flow. As such, this study approximates the actual assembly using an equivalent one-dimensional assembly comprising only thermal resistances connected in

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

[4] $Total\ Assembly\ R - value = (\frac{FF}{R_{stud\ path}} + \frac{1-FF}{R_{cavity\ path}})^{-1}$

series. To achieve this, an equivalent resistance of the layer comprised of studs and cavity insulation was calculated by subtracting the R-values of the continuous elements from the total R-value of the assembly. For example, for climate zone 3 the equivalent R-value of the stud/cativy insulation section is 9.88 (i.e., 16.08-0.20-5.00-0.54-0.45 = 9.88). similarly, for climate zone 5 the equivalent R-value of the stud/cavity insulation section is 10.21. Table 6 shows the equivalent effective R-value and insulation thickness inputted to the EnergyPlus models for the insulation layers, where "wall_consol_layer" is the representative layer for the stud/cavity insluation section. The structural and finish layers were unaltered from the original prototypical model.

Table 6: Equivalent Effective R-Value and Thickness Values of the Insulation Layers in the Exterior Wall

Insulation Layer	CZ3		CZ5	
	Effective R-value	Thickness, inch (m)	Effective R-value	Thickness, inch (m)
sheathing_consol_layer (50/50 XPS/EPS)	5.00	1.11 (0.0282)	10.00	2.22 (0.0564)
wall_consol_layer (50/50 oc-SPF/cc-SPF)	9.88	1.98 (0.0502)	10.21	2.04 (0.0519)

B. Basement Exterior Wall

This study altered the assumptions used by PNNL for basement wall construction to better align with typical wall assembly for heated basements. Table 7 shows the construction layers of the basement exterior wall and their R-values. The construction layers are divided into two groups: the structural and finish layers (e.g., 8" concrete wall and drywall) and the insulation layers (shown in bold in the table).

Table 7: R-Values of Construction Layers of Basement Exterior Wall (Starting from the Outer Layer)

Construction Layer	CZ3	CZ5
Exterior Insulation (XPS)	**5.00**	**10.00**
8" Concrete Wall	0.67	0.67
Interior Insulation* (50/50 XPS/EPS)	**-**	**5.00**
Drywall_1/2in	0.45	0.45
Total R-value	6.12	16.12

*** A minimum of R-5ci is required for CZ3 and R-15ci is required for CZ5**

Table 8 shows the equivalent effective R-value and insulation thickness inputted to the EnergyPlus models for the construction layers.

Table 8: Equivalent Effective R-Value and Thickness Values of the Insulation Layers in the Basement Exterior Wall

Insulation Layer	CZ3		CZ5	
	Effective R-value	Thickness, inch (m)	Effective R-value	Thickness, inch (m)
Exterior Insulation (XPS)	5.00	1.00 (0.0254)	10.00	2.00 (0.0508)
Interior Insulation (50/50 XPS/EPS)	-	-	5.00	1.00 (0.0254)

C. Roof

The PNNL models simulate the case with vented unconditioned attics where the insulation requirements are applied to the attic floor. This study investigated the case with an unvented unconditioned attic where the insulation is applied under the roof deck and exterior side walls of the attic (i.e., gable end walls). This study assumes a wood-frame roof comprising 2x4 studs 24 inch on center (O.C.) for the roof truss top chord members. For the purposes of this study, framing factor (FF) of the roof was assumed to be 10%[5]. Then, two parallel heat flow paths were developed to calculate the insulation effective R-value that is used in the EnergyPlus models. Table 9 shows the construction layers of the roof and their R-values along the studs path and the cavity path. The construction layers are divided into two groups: the structural and finish layers (e.g., shingles) and the insulation layers (shown in bold in the table).

Table 9: R-Values of Construction Layers of Roof through Studs Path and Cavity Path (Starting from the Outer Layer)

Construction Layer	CZ3		CZ5	
	Studs Path	Cavity Path	Studs Path	Cavity Path
ashphalt_shingle	0.44	0.44	0.44	0.44
OSB_1/2in	0.62	0.62	0.62	0.62
wood studs	4.38		4.38	
roof insulation_cavity (cc-SPF)		**22.75**		**22.75**
roof insulation_continuous (cc-SPF)	**15.25**	**15.25**	**26.25**	**26.25**
Total R-value	20.69	39.06	31.69	50.06

Following the same methodology as with the exterior wall insualtion, the total R-values of the assembly were calculated to be 35.87[4] and 47.32 for climate zones 3 and 5, respectively. The equivalent R-value of the roof joists section were found to be 34.81 and 46.26 for climate zones 3 and 5, respectively. Table 10 shows the equivalent R-value and insulation thickness inputted to

[5] Hogan, J F. Approach for opaque envelope U-factors for ASHRAE/IESNA 90.1-1989R. United States: N. p., 1995. Web.

the EnergyPlus models for the insulation layers. The structural and finish layers were unaltered from the original prototypical model. It can be noted here that the thickness of the spray foam insulation extends beyond the 3.5" depth of the cavity, thereby modeled as a layer of continuous insulation covering the studs section.

Table 10: Equivalent Effective R-Value and Thickness Values of the Insulation Layers in the Roof

Insulation Layer	CZ3		CZ5	
	Effective R-value	Thickness, inch (m)	Effective R-value	Thickness, inch (m)
Roof insulation (cc-SPF) Cavity + Continuous	34.81	5.36 (0.136)	46.26	7.12 (0.181)

C. Gable End Wall

This study assumes a wood-frame attic gable end wall comprising 2x4 studs 24 inch on center (O.C.). This translates into a framing factor (FF) of 22%[3]. Then, two parallel heat flow paths were developed to calculate the insulation effective R-value that is used in the EnergyPlus models. Table 11 shows the construction layers of the gable end wall and their R-values along the studs path and the cavity path. The construction layers are divided into two groups: the structural and finish layers (e.g., stucco, wood studs and drywall) and the insulation layers (shown in bold in the table).

Table 11: R-Values of Construction Layers of Gable End Wall through Studs Path and Cavity Path (Starting from the Outer Layer)

Construction Layer	CZ3		CZ5	
	Studs Path	Cavity Path	Studs Path	Cavity Path
syn_stucco	0.20	0.20	0.20	0.20
sheathing_consol_layer (50/50 XPS/EPS)	**5.00**	**5.00**	**10.00**	**10.00**
OSB_7/16in	0.54	0.54	0.54	0.54
wood studs	4.38		4.38	
wall_consol_layer (50/50 oc-SPF/cc-SPF)		**13.00**		**13.00**
air cavity_1in		0.26		0.26
drywall_1/2in	0.45	0.45	0.45	0.45
Total R-value	10.57	19.45	15.57	24.45

The effective R-values of the assembly and the cavity were then calculated to be 16.42[4] and 10.23, respectively for climate zone 3 and 21.73 and 10.53, respectively for climate zone 5. Table 12 shows the equivalent R and thickness values inputted to the EnergyPlus models for the insulation layers, where "wall_consol_layer" is the representative layer for the stud/cavity insluation section. The structural and finish layers were unaltered from the original prototypical model.

Table 12: Equivalent Effective R-Value and Thickness Values of the Insulation Layers in the Gable End Wall

Insulation Layer	CZ3		CZ5	
	Effective R-value	Thickness, inch (m)	Effective R-value	Thickness, inch (m)
sheathing_consol_layer (50/50 XPS/EPS)	5.00	1.11 (0.0282)	10.00	2.22 (0.0564)
wall_consol_layer (50/50 oc-SPF/cc-SPF)	10.23	2.05 (0.0520)	10.53	2.11 (0.0535)

In the simulated scenarios where there is no insulation on one or more of the envelope components the insulation layers were deleted from the assembly construction in the respective models. For example, scenario R3 simulates the case with no basement exterior wall insulation. As such, in this scenario, both the exterior and interior insulation layers were removed from the assembly model and only the 8" concrete wall and the ½" drywall were retained.

3.2.2 Commercial Prototype: Medium Office Building

The prototypical building characteristics for the medium office building are as follows:

Building Size: 3-story office building with a conditioned area of 53,600 ft^2

Foundation Type: Slab on grade

HVAC Systems: Packaged Air Unit per floor

- Air Conditioning: 2-speed DX Cooling Coil
- Heating: Gas Furnace (81% Efficiency + Electric Resistance Reheat)

ACC was interested in exploring the impact of the following five scenarios, shown in Table 13, on the energy and GHG emissions over 75-year lifetime of the plastic insulation materials. Note here that "C" in the scenario label stands for "Commercial".

Table 13: Simulated Scenarios for Commercial Prototype

Scenario	Description
C0	No Insulation (Baseline)
C1	Slab Perimeter + Roof Insulation (No Wall Insulation)
C2	Wall + Roof Insulation (No Slab Perimeter Insulation)
C3	Wall + Slab Perimeter Insulation (No Roof Insulation)
C4	Whole Office Insulation

Table 14 shows the minimum insulation prescriptive R-values required by ASHRAE 90.1 – 2019 standards for the different envelope components in climate zones 3 and 5. Upon consultation with ACC and reviewing common practices in commercial building insulation, Table 14 shows the selected insulation materials assumed for each component.

Table 14: ASHRAE 90.1 – 2019 Minimum Insulation R-Values for Different Envelope Components in Climate Zones 3 and 5

Location	Climate Zone	
	CZ 3	CZ 5
Above-grade Wall Insulation	Steel framed, R-13 cc-SPF in cavity, R-5ci Polyiso foam sheathing	steel framed, R-13 cc-SPF in cavity, R-10ci Polyiso foam sheathing
Slab Perimeter Insulation	None	R-15ci XPS foam sheathing for 24" deep from top of slab down
Roof Insulation (Entirely Above Deck)	R-25ci Polyiso foam sheathing	R-30ci Polyiso foam sheathing

The prototypical building models were reviewed and adapted to ensure the conformance of the envelope compoments' construction with the ASHRAE 90.1 – 2019 standards requirements. The following section details the breakdown of the construction layers of the envelope components.

A. Above-grade Exterior Wall

This study assumes a 16-inch O.C. steel-frame exterior wall. COMcheck Technical Documentation[6] suggests the following equation to estimate the assembly R-value:

$$R_{Assembly} = CF \times R_{Cavity} + R_{Continuous}$$

Where, CF is the correction factor applied to the R-value of the cavity insulation to account for the steel framing such that CF x R_{cavity} represents an effective R-value for the cavity and framing layer of the assembly. R_{Cavity} is the R-value for cavity insulation and $R_{Continuous}$ is the R-value of the continuous insulation layer. Thus, $R_{Assembly}$ is the effective R-value for the assembly with a U-factor equal to $1/R_{Assembly}$. The CF for 16-in O.C. steel frame with R-13 cavity insulation can be assumed to be 0.46, resulting in an effective R-value for the cavity layer of: 0.46 x 13 = 5.98. Table 15 shows the construction layers of the exterior wall and their R-values. The construction layers are divided into two groups: the structural and finish layers (e.g., stucco and gypsum board) and the insulation layers (shown in bold in the table).

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

Table 15: R-Values of Construction Layers of Exterior Wall (Starting from the Outer Layer)

Construction Layer	CZ3	CZ5
F07 25mm stucco	0.20	0.20
sheathing_consol_layer (Polyiso)	**5.00**	**10.00**
G01 16mm gypsum board	0.56	0.56
Nonres_Exterior_Wall_Insulation (cc-SPF)*	**5.98**	**5.98**
G01 16mm gypsum board	0.56	0.56
Total R-value	12.31	17.31

*** Cavity insulation with reduction factor applied to account for framing.**

Table 16 shows the equivalent effective R-value and thickness values inputted to the EnergyPlus models for the insulation layers. The structural and finish layers were unaltered from the original prototypical model.

Table 16: Equivalent Effective R-Value and Thickness Values of the Insulation Layers in the Exterior Wall

Insulation Layer	CZ3		CZ5	
	Effective R-value	Thickness, inch (m)	Effective R-value	Thickness, inch (m)
sheathing_consol_layer (Polyiso) - continuous insulation layer	5.00	0.86 (0.0219)	10.00	1.72 (0.0438)
Nonres_Exterior_Wall_Insulation (cc-SPF)*	5.98	0.92 (0.0234)	5.98	0.92 (0.0234)

*** Cavity insulation and framing material**

B. Slab on Grade

The prototypical models simulate the heat loss (and annual energy use) of an entire slab area and its perimeter edges using a linear thermal transmittance value, known as an F-factor, associated with the length of the slab perimeter. The F-factor is normalized to account for ground contact heat loss (as well as direct air-to-air heat loss at the slab perimeter) and it associates all heat loss with the outdoor air temperature differential only (not ground temperature differential). It also is specific to a slab configuration having a 9:1 ratio of slab surface area to perimeter length and an edge projection above grade of 6 inches, although in practice the F-factor is commonly more broadly applied beyond these conditions resulting in under estimation of energy use for slabs having a larger area to peremiter ratio or greater projection above exterior grade (and vice-versa). Thus, for many commercial building applications with large slab areas, this approach may result in under-estimation of actual energy saving associated with slab-on-grade insulation, particularly for slabs with under slab insulation and perimeter edge insulation. In EnergyPlus modeling, this approach is called the F-factor method[7]. This method models the heat transfer between the indoor space and the outdoors through the slab as:

$$Q = (T_{air\ outside} - T_{air\ inside}) \times P_{expos} \quad \times F - factor$$

Where, Q is the rate of heat transfer, $T_{air\ outside}$ is the outdoor temperature, $T_{air\ inside}$ is the indoor temperature, and $P_{exposed}$ is the exposed perimeter of the slab. ASHRAE 90.1 – 2019 standards specify maximum value of F-factor to be 0.73 (i.e., uninsulated, unheated slab) for climate zone 3 and 0.52 for climate zone 5 (an insulated, unheated slab with only vertical perimeter insulation of R-15 for 24" depth at slab edge). These values were populated in the EnergyPlus models for all simulated scenarios.

C. Roof

This study assumes a continuous insulation layer that is entirely above deck. Table 17 shows the construction layers of the roof and their R-values. The construction layers are divided into two groups: the structural and finish layers (e.g., built-up roofing and metal surface) and the insulation layers (shown in bold in the table).

Table 17: R-Values of Construction Layers of Roof (Starting from the Outer Layer)

Construction Layer	CZ3	CZ5
F13 Built-up roofing	0.34	0.34
Nonres_Roof_Insulation (Polyiso)	**25.00**	**30.00**
F08 Metal surface	0.00	0.00
Total R-value	25.34	30.34

Table 18 shows the equivalent effective R-value and thickness values inputted to the EnergyPlus models for the insulation layers. The structural and finish layers were unaltered from the original prototypical model.

[7] https://bigladdersoftware.com/epx/docs/8-7/engineering-reference/ground-heat-transfer-calculations-using-c.html

Table 18: Equivalent Effective R-Value and Thickness Values of the Insulation Layers in the Roof

Insulation Layer	CZ3		CZ5	
	Effective R-value	Thickness, inch (m)	Effective R-value	Thickness, inch (m)
Nonres_Roof_Insulation (Polyiso)	25.00	4.31 (0.109)	30.00	5.17 (0.130)

3.3 Model Simulations

Prior to running the final simulations, the PNNL models were simulated unaltered, and the results were compared against those published by PNNL. Only slight deviations were noticed, most likely due to differences in EnergyPlus version used in this study (the latest EnergyPlus software V23.1) and those used by PNNL (V9.5 for residential prototypes and V9.0 for commercial prototypes). ICF ran a total of 147 simulations which are broken down as follows:

A. Residential Prototype – Single-family Detached Home

6 Climate Zones x 4 Heating Systems x 5 Scenarios = 120 Simulations

B. Commercial Prototype – Medium Office Building

6 Climate Zones x 5 Scenarios – 3 Scenarios (CZ3 does not require slab insulation) = 27 Simulations

Each simulation took an average of two to three minutes computational time to complete. A few simulations displayed an error in the warm up period pertaining to the effect of lower thermal mass of the building causing the temperature iterations to not meet the convergence criteria. This error was mitigated by setting the minimum density of the insulation materials to 1.87 lb/ft^3 instead of 1.56 lb/ft^3. A separate test was also conducted to isolate the effect of density variance on the results. The test showed the impact of changing the density of the insulation material to be insignificant.

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: electricity, natural gas and fuel oil, and by end use (e.g., heating, cooling, lighting, etc.). Realizing that the envelope insulation only impacts the heating and cooling end uses, results for all other non-weather sensitive end uses were grouped together under "Other End Uses".

In order to properly evaluate the GHG emission savings attributed to envelope insulation, source energy use was derived from site energy use using the following source-site ratios:

Table 19: Source-Site Ratios of Different Fuel Types[8]

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

The results were aggregated for each climate zone by applying weighted averaging of the results from the three moisture regimes. Weighting factors for each of single-family detached homes were developed for the climate zones using the Residential Energy Consumption Survey (RECS 2020)[9]. Table 20 shows the weighting factors for each climate zone.

Table 20: Weighting Factors for Single-family Detached Homes in Climate Zones 3 and 5

Moisture Regime	Climate Zone	
	CZ3	**CZ5**
A	61%	86%
B	31%	16%
C	8%	8%

Due to lack of data on the stock distribution of medium office buildings across the different climate zones, a uniform distribution was used to calculate the climate zone average results.

For the residential prototype, the results for an average single-family detached home were calculated by applying weighted averaging of the results from prototypes with different heating systems (i.e., electric resistance furnace, natural gas furnace, fuel oil furnace and electric heat pump). Two scenarios were explored:

1. Scenario 1: A scenario that assumes that the current distribution of heating systems prevails over the time horizon of the study (i.e., 75 years). Table 21 displays the current weighting factors of the four different heating systems.

[8] 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

[9] https://www.eia.gov/consumption/residential/data/2020/

Table 21: Weighting Factors for Single-family Detached Homes with Different Heating Systems[8]

Heating System	Climate Zone	
	CZ3	CZ5
Electric Resistance Furnace	2%	2%
Natural Gas Furnace	28%	74%
Fuel Oil Furnace	0%	3%
Electric Heat Pump	70%	21%

2. Scenario 2: A scenario that assumes the full transition into heat pump heating systems. This scenario zeros the weight of the other three heating systems, thereby provides a bookend case of heating electrification with 100% heat pump proliferation.

For the commercial prototype, two scenarios were explored:

1. Scenario 1: A scenario that assumes that the natural gas heating system prevails over the time horizon of the study (i.e., 75 years).
2. Scenario 2: A scenario that 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[10] were utilized. Upon consultation with ACC, the emission rates for the state of Georgia were chosen as a conservative representation of emissions from the electricity generation in climate zones 3 and 5 in comparison to the variation of regional emission rates within those climate zones. 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. Low RE Cost scenario assumes the cost of converting our grid to a renewable energy grid is relatively low while High RE Cost scenario assumes the cost of converting our grid to renewable energy is high and therefore more difficult. Table 22 shows the electricity emission rates generated by Cambium for Georgia for the three RE cost scenarios. Since the Cambium database

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

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). Linear interpolation was applied between the datapoints in Table 22 to obtain the emission rates for the intermediate years.

Table 22: Electricity Emission Rates for Three Scenarios: Low RE Cost, Medium RE Cost, and High RE Cost

Year	Electricity Emission Rate (kg CO_2e/MWh)		
	High RE Cost	Medium RE Cost	Low RE Cost
2024	327.0	302.7	255.0
2026	342.4	266.7	234.0
2028	330.5	211.6	176.1
2030	324.1	188.7	97.9
2035	325.0	132.1	40.8
2040	313.2	87.8	25.2
2045	315.8	63.7	39.6
2050	282.6	57.6	34.9

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[11].

In order to calculate the carbon payback period and carbon avoidance ratio, embodied carbon data for the plastic insulation materials was obtained from ACC. Table 23 lists contemporary representative values of the full life-cycle embodied carbon for the different insulation materials employed in the simulations. The embodied carbon of insulation materials is expressed in kg CO_2e/m^2 in accordance with the Product Category Rule's defined Functional Unit (FU) of 1 m^2 of material with an RSI = 1.0.

The representative values selected are based on the values associated with current generation materials which have lower amounts of embodied carbon than previous generations of materials. Many materials with higher embodied carbon have been phased out or are in process of being phased out. All values are taken from third party, publicly available Environmental Product Declarations (EPDs).

XPS values were based on the average EPD values from four North American manufacturers. EPS values were based on the values for EPS Types I, II, and IX in the industry average EPD. The Types are representative of the Types used in the applications included in this study. Polyiso wall values were based on the averaged EPD values from two manufactures. Polyiso roof values were based on the averaged EPD values from 3 manufactures. The embodied carbon values of cc-SPF and oc-SPF were based on the industry wide EPD. Where a 50/50 blend of materials was used to account for applications where the use of one of two different materials is likely, the values of those two materials were averaged to come up with a representative value.

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

Table 23: Embodied Carbon Per Functional Unit of Plastic Insulation Materials

Insulation Material	Embodied Carbon (kg CO_2e/m^2)
XPS	5.63
EPS	3.78
Polyiso (Wall)	3.49
Polyiso (Roof)	3.46
cc-SPF	4.21
oc-SPF	1.68
50/50 XPS/EPS	4.71
50/50 cc-SPF/oc-SPF	2.95

The embodied carbon values presented in the table above are per unit functional unit (FU) of the insulation material, which is equivalent to 1 m^2 of insulation with a thickness corresponding to RSI-1.0. As such, the total embodied carbon of the insulation materials applied to each envelope component was calculated using:

$$Embodied\ Carbon = Embodied\ Carbon\ per\ FU \times \frac{t_{insulation}}{t_{RSI=1}} \times A_{surface} \times (1 - FF\%)$$

Where, $t_{insulation}$ is the actual thickness of the insulation used in the simulations, $t_{RSI=1}$ is the thickness of the insulation equivalent to RSI-1.0, $A_{surface}$ is the surface area of the envelope component to which the insulation is applied, FF is the framing factor of the envelope component to which the insulation is applied. The FF is applied differently for wood framing and steel framing due to differences in the thickness of the framing members (e.g., steel stud webs being at most a couple millimeters thick resulting in a greater volume of cavity insulation for a similar stud spacing yet also causing greater heat transfer as represented by a "cavity correction factor" rather than use of a framing factor to determine the effective R-Value).

The annual source energy savings were converted into the annual GHG savings using the emission rates of the different fuel types. Then, the carbon payback period and carbon lifetime operational savings to embodied carbon ratio (hereafter referred to as "carbon avoidance ratio") were evaluated using the following formulas:

$$Carbon\ Payback\ Period\ (months) = N, \qquad for\ Embodied\ Carbon = \sum_{1}^{N} Monthly\ GHG\ Savings$$

$$Carbon\ Avoidance\ Ratio = \frac{\sum_{1}^{75} Annual\ GHG\ Savings}{Embodied\ Carbon}$$

Where, the $Monthly\ GHG\ Savings$ are calculated assuming uniform savings across the year:

$$Monthly\ GHG\ Savings = \frac{1}{12} \times Annual\ GHG\ Savings$$

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

This section starts by analyzing the impact of the insulation scenarios on the energy consumption and savings, followed by the analysis of the impacts on the GHG savings. The main objective of this section is to highlight the impact of applying insulation to different envelope components on the carbon payback period and carbon avoidance ratio.

4.1.1 Energy Accounting

4.1.1.1 Scenario 1: Current Heating Systems Mix

This scenario assumes that the current distribution of heating systems prevails over the time horizon of the study (75 years). The results were averaged using the weighting factors from Table 21. (Recall that "R" and "C" in the scenario label stand for Residential and Commercial, respectively)

Table 24 and Figure 1 show the electricity end use consumption for the different insulation scenarios in climate zones 3 and 5. The units of kBtu are used for electricity instead of kWh to remain consistent with units for energy used for natural gas and fuel oil (3.4 kBtu = 1 kWh if approximate conversion is desired). Table 25, Table 26 and Figure 2 show the contribution of insulation on individual envelope elements, quantified by comparing the consumption of each insulation scenario to that of R4 (full home insulation). For example, subtracting the electricity consumption of scenario R4 from that of scenario R3 (i.e., no attic insulation) provides an estimate of the impact of removing the attic insulation. The larger the value of the savings, the greater the contribution of the insulation of the respective envelope element.

Table 24: Electricity Consumption by End Use, Climate Zone and Insulation Scenario for the Case with Current Heating Systems Mix (Residential Prototype)

CZ	Scenario	Electricity Consumption [kBtu]					
		Heating	Cooling	Fans	Water Systems	Other	Total End Uses
CZ3	R0 – No Insulation	29,084	18,897	10,169	2,253	35,730	96,132
	R1 – Basement + Attic Insulation (No Wall Insulation)	18,957	14,053	7,159	2,248	35,730	78,146
	R2 – Wall + Attic Insulation (No Basement insulation)	8,738	7,886	3,725	2,244	35,730	58,322
	R3 – Wall + Basement Insulation (No Attic Insulation)	15,507	10,973	5,691	2,246	35,730	70,146
	R4 – Fully Insulated Home (Whole Home Insulation)	6,750	7,026	3,174	2,241	35,730	54,920
CZ5	R0 – No Insulation	41,005	7,667	12,739	1,163	38,151	100,724
	R1 – Basement + Attic Insulation	25,477	6,608	9,258	1,161	38,151	80,654

	(No Wall Insulation)						
	R2 – Wall + Attic Insulation (No Basement insulation)	13,269	3,264	4,226	1,157	38,151	60,067
	R3 – Wall + Basement Insulation (No Attic Insulation)	21,571	4,936	7,219	1,160	38,151	73,037
	R4 – Fully Insulated Home (Whole Home Insulation)	8,744	3,629	3,797	1,157	38,151	55,477

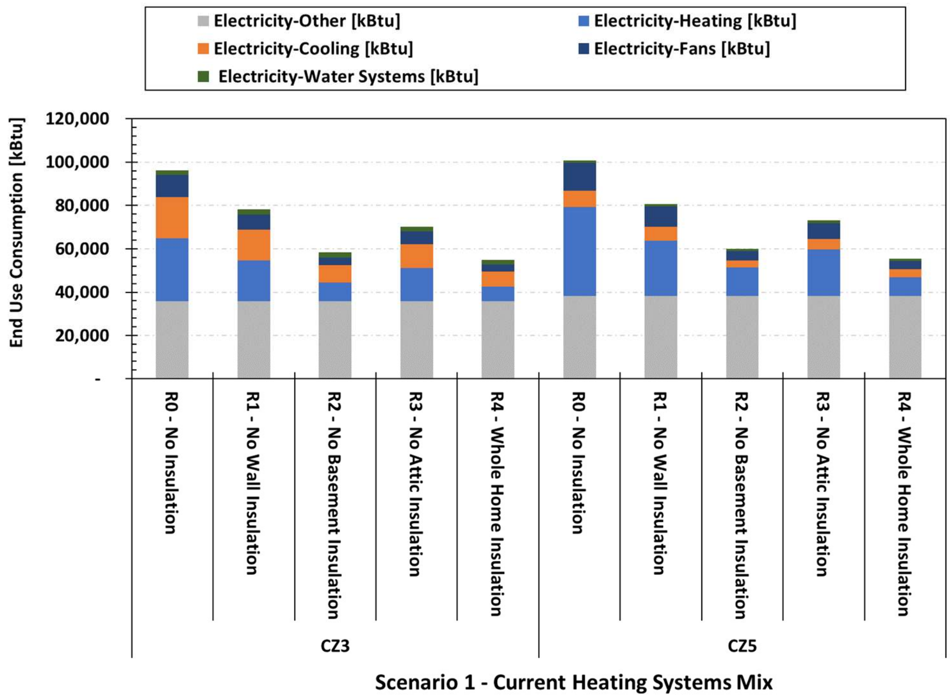

Figure 1: Electricity End Use Consumption for the Case with the Current Heating Systems Mix

As expected, the results show that the insulation has a large impact on the heating and cooling consumptions. Comparing R0 (no insulation) to R4 (fully insulated), it is seen that the heating consumption for the fully insulated scenario dropped by 77% for CZ3 and 79% for CZ5, while cooling consumption dropped by 63% for CZ3 and 53% for CZ5. Also, the HVAC system fan consumption dropped by around 70%. The electric consumption of the hot water system was slightly affected (~1% drop) likely due to the decreased thermal losses in winter from the water tank and pipes to the insulated spaces.

Comparing CZ3 to CZ5, the latter exhibits higher heating consumption and lower cooling consumption due to the cooler climate, yielding a net positive increase in total electricity consumption. This also results in larger savings in heating consumption and lower savings in cooling consumption in CZ5 relative to CZ3, as shown in Table 25 and Figure 2, due to the cooler climate and space heating being the dominant contributor to total energy consumption. One interesting observation on scenario R2 (no basement insulation) in CZ5 was that it exhibited lower cooling consumption compared to R4 (full home insulation). Such behavior was verified and is likely attributed to the free cooling imparted by the cool soil surrounding the uninsulated basement walls during summer, resulting in less cooling load on the HVAC system.

It is seen that the wall insulation has the largest impact on the savings, followed by the attic insulation, then the basement wall insulation. This observation aligns with the expectations since the exterior wall area is around 1.5 times that of the attic area. Also, the basement wall insulation has the smallest effect due to the inherent insulation properties of the surrounding soil. Note that the savings from isolated insulation components (wall, roof, basement) do not add up to the total "whole home" impact, due to interactive effects between the components.

Table 25: Impact of Insulation on Electricity Savings by End Use and Climate Zone for the Case with Current Heating Systems Mix (Residential Prototype)

CZ	Scenario	Electricity Savings [kBtu]				
		Heating	Cooling	Fans	Water Systems	Total End Uses
CZ3	Whole Home Insulation Impact	22,334[12]	11,871	6,995	11	41,212
	Wall Insulation Impact	12,207	7,027	3,985	7	23,226
	Basement Insulation Impact	1,988	860	551	2	3,402
	Attic Insulation Impact	8,757	3,947	2,517	4	15,226
CZ5	Whole Home Insulation Impact	32,261	4,037	8,942	6	45,246
	Wall Insulation Impact	16,733	2,979	5,461	4	25,177
	Basement Insulation Impact	4,525	-365	429	1	4,590
	Attic Insulation Impact	12,828	1,307	3,422	3	17,560

[12] Electricity Savings (Whole Home Insulation Impact) = R0 (No Insulation) Electricity Consumption - R4 (Whole Home Insulation) Electricity Consumption {The same formula is used for individual insulation elements by replacing R0 Electricity Consumption in the Equation with those for R1, R2, and R3}

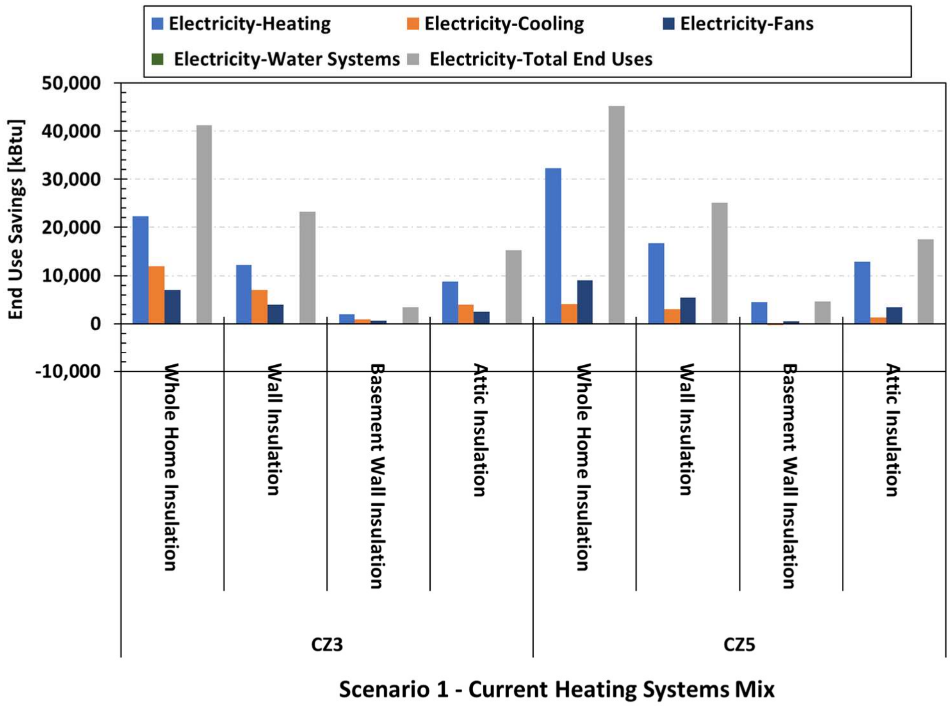

Figure 2: Impact of Insulation on Electricity End Use Savings for the Case with the Current Heating Systems Mix

Table 26 demonstrates the percent electricity savings from individual envelope elements compared to the case with whole building insulation. The values presented in the table and the figure do not reflect the magnitudes of savings, rather the relative impact of insulation on individual envelope elements. Again, the sum of the individual components is greater than the whole home total, due to interactive impacts between insulation components.

Table 26: Electricity Percent Savings by End Use, Climate Zone and Insulation Scenario for the Case with Current Heating Systems Mix (Residential Prototype)

CZ	Scenario	Electricity Savings [%]				
		Heating	Cooling	Fans	Water Systems	Total End Uses
CZ3	Whole Home Insulation Impact	100%	100%	100%	100%	100%
	Wall Insulation Impact	55%[13]	59%	57%	63%	56%
	Basement Insulation Impact	9%	7%	8%	20%	8%
	Attic Insulation Impact	39%	33%	36%	40%	37%
CZ5	Whole Home Insulation Impact	100%	100%	100%	100%	100%
	Wall Insulation Impact	52%	74%	61%	66%	56%
	Basement Insulation Impact	14%	-9%	5%	10%	10%
	Attic Insulation Impact	40%	32%	38%	47%	39%

[13] $\text{Electricity Savings\% (Wall Insulation Impact)} = \frac{\text{Electricity Savings (Wall Insulation)}}{\text{Electricity Savings (Whole Home Insulation)}}\%$

Natural gas consumption in homes is primarily attributed to space heating, hot water and cooking end uses. Table 27 to Table 29, and Figure 3 and Figure 4 show trends similar to those in electricity consumption and savings results.

Table 27: Natural Gas Consumption by End Use, Climate Zone and Insulation Scenario for the Case with Current Heating Systems Mix (Residential Prototype)

CZ	Scenario	Natural Gas Consumption [kBtu]			
		Heating	Water Systems	Other	Total End Uses
CZ3	R0 – No Insulation	36,481	2,407	3,084	41,972
	R1 – Basement + Attic Insulation (No Wall Insulation)	22,202	2,407	3,084	27,693
	R2 – Wall + Attic Insulation (No Basement insulation)	8,864	2,407	3,084	14,355
	R3 – Wall + Basement Insulation (No Attic Insulation)	17,926	2,407	3,084	23,417
	R4 – Fully Insulated Home (Whole Home Insulation)	6,225	2,407	3,084	11,716
CZ5	R0 – No Insulation	249,339	9,278	8,802	267,419
	R1 – Basement + Attic Insulation (No Wall Insulation)	153,449	9,278	8,802	171,530
	R2 – Wall + Attic Insulation (No Basement insulation)	69,777	9,278	8,802	87,857
	R3 – Wall + Basement Insulation (No Attic Insulation)	124,946	9,278	8,802	143,026
	R4 – Fully Insulated Home (Whole Home Insulation)	45,447	9,278	8,802	63,527

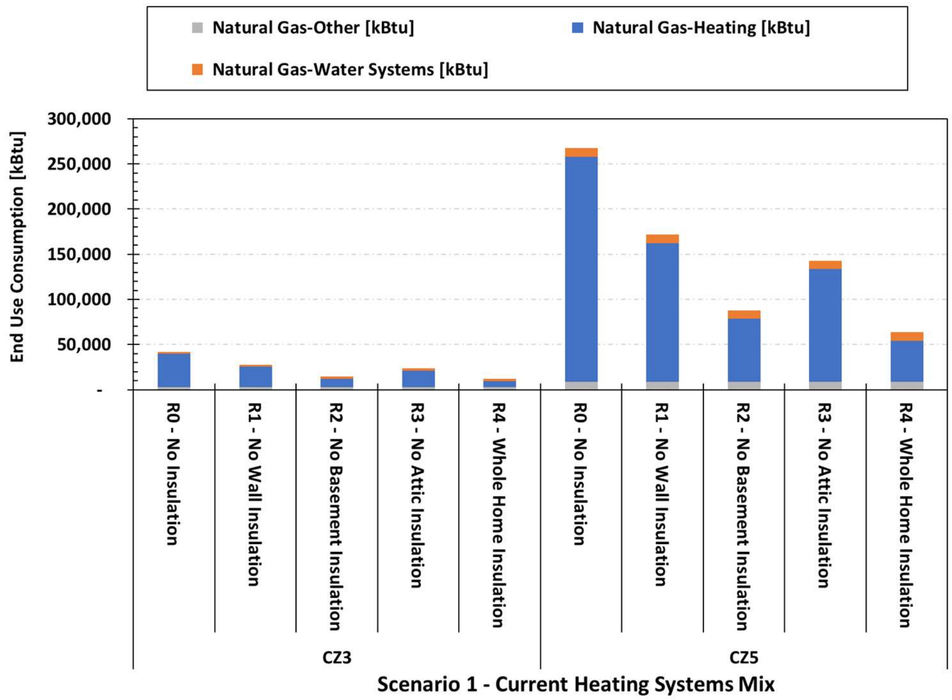

Figure 3: Natural Gas End Use Consumption for the Case with the Current Heating Systems Mix (residential)

Table 28: Impact of Insulation on Natural Gas Savings by End Use and Climate Zone for the Case with Current Heating Systems Mix (Residential Prototype)

CZ	Scenario	Natural Gas Savings [kBtu]	
		Heating	Total End Uses
CZ3	Whole Home Insulation Impact	30,256[14]	30,256
	Wall Insulation Impact	15,977	15,977
	Basement Insulation Impact	2,638	2,638
	Attic Insulation Impact	11,701	11,701
CZ5	Whole Home Insulation Impact	203,892	203,892
	Wall Insulation Impact	108,002	108,002
	Basement Insulation Impact	24,329	24,329
	Attic Insulation Impact	79,499	79,499

[14] Natural Gas Savings (Whole Home Insulation Impact) = R0 (No Insulation) Natural Gas Consumption – R4 (Whole Home Insulation) Natural Gas Consumption {The same formula is used for individual insulation elements by replacing R0 Natural Gas Consumption in the Equation with those for R1, R2, and R3}

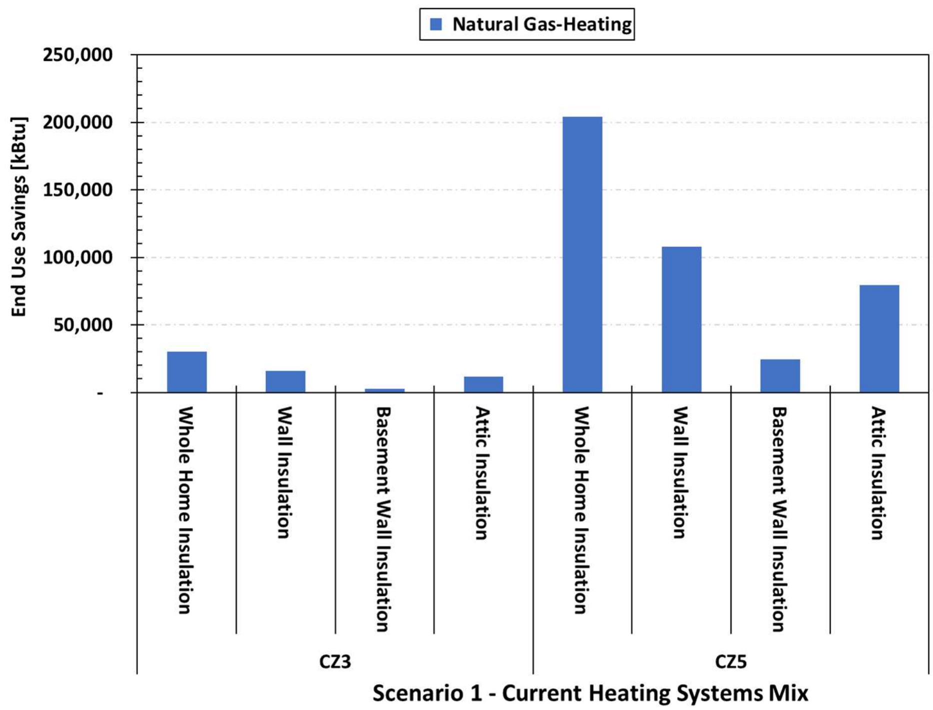

Figure 4: Impact of Insulation on Natural Gas End Use Savings for the Case with the Current Heating Systems Mix

Table 29: Natural Gas Percent Savings by End Use, Climate Zone and Insulation Scenario for the Case with Current Heating Systems Mix (Residential Prototype)

CZ	Scenario	Natural Gas Savings [%]	
		Heating	Total End Uses
CZ3	Whole Home Insulation Impact	100%	100%
	Wall Insulation Impact	53%[15]	53%
	Basement Insulation Impact	9%	9%
	Attic Insulation Impact	39%	39%
CZ5	Whole Home Insulation Impact	100%	100%
	Wall Insulation Impact	53%	53%
	Basement Insulation Impact	12%	12%
	Attic Insulation Impact	39%	39%

Only 3% of new single-family homes in climate zone 5 uses fuel oil furnaces for space heating (see Table 21). Table 30 to Table 32, and Figure 5 and Figure 6 show similar trends for fuel oil end use consumption and savings.

[15] $\text{Natural Gas Savings\% (Wall Insulation Impact)} = \frac{\text{Natural Gas Savings (Wall Insulation)}}{\text{Natural Gas Savings (Whole Home Insulation)}}\%$

Table 30: Fuel Oil Consumption by End Use, Climate Zone and Insulation Scenario for the Case with Current Heating Systems Mix (Residential Prototype)

CZ	Scenario	Fuel Oil Consumption [kBtu]	
		Heating	Total End Uses
CZ3	R0 – No Insulation	–	–
	R1 – Basement + Attic Insulation (No Wall Insulation)	–	–
	R2 – Wall + Attic Insulation (No Basement insulation)	–	–
	R3 – Wall + Basement Insulation (No Attic Insulation)	–	–
	R4 – Fully Insulated Home (Whole Home Insulation)	–	–
CZ5	R0 – No Insulation	10,702	10,702
	R1 – Basement + Attic Insulation (No Wall Insulation)	6,700	6,700
	R2 – Wall + Attic Insulation (No Basement insulation)	3,214	3,214
	R3 – Wall + Basement Insulation (No Attic Insulation)	5,554	5,554
	R4 – Fully Insulated Home (Whole Home Insulation)	2,193	2,193

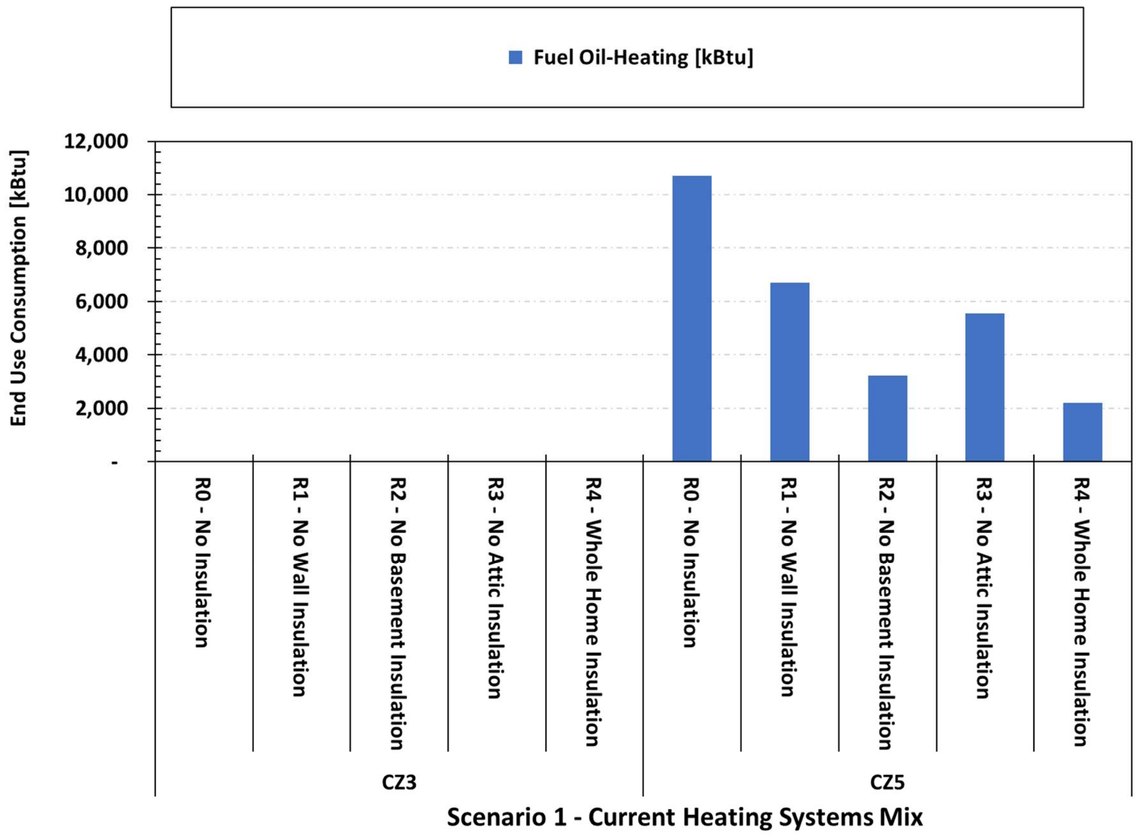

Figure 5: Fuel Oil End Use Consumption for the Case with the Current Heating Systems Mix

Table 31: Impact of Insulation on Fuel Oil Savings by End Use and Climate Zone for the Case with Current Heating Systems Mix (Residential Prototype)

CZ	Scenario	Fuel Oil Savings [kBtu]	
		Heating	Total End Uses
CZ3	Whole Home Insulation Impact	-	-
	Wall Insulation Impact	-	-
	Basement Insulation Impact	-	-
	Attic Insulation Impact	-	-
CZ5	Whole Home Insulation Impact	8,509[16]	8,509
	Wall Insulation Impact	4,508	4,508
	Basement Insulation Impact	1,021	1,021
	Attic Insulation Impact	3,361	3,361

[16] Fuel Oil Savings (Whole Home Insulation Impact) = R0 (No Insulation) Fuel Oil Consumption - R4 (Whole Home Insulation) Fuel Oil Consumption {The same formula is used for individual insulation elements by replacing R0 Fuel Oil Consumption in the Equation with those for R1, R2, and R3}

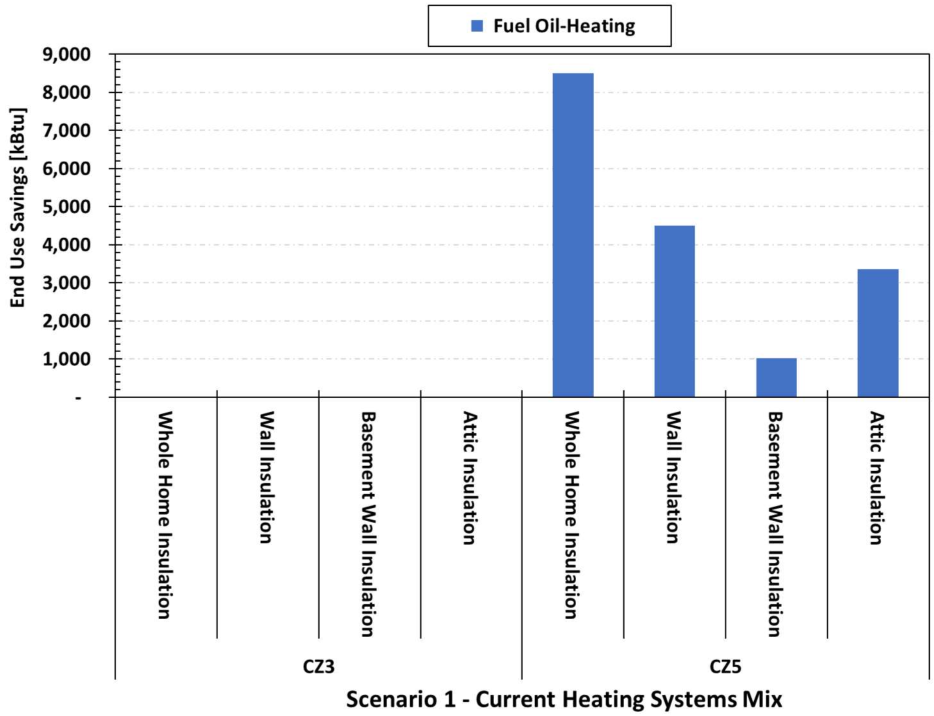

Figure 6: Impact of Insulation on Fuel Oil End Use Percent Savings for the Case with the Current Heating Systems Mix

Table 32: Fuel Oil Percent Savings by End Use, Climate Zone and Insulation Scenario for the Case with Current Heating Systems Mix (Residential Prototype)

CZ	Scenario	Fuel Oil Savings [%]	
		Heating	Total End Uses
CZ3	Whole Home Insulation Impact	-	-
	Wall Insulation Impact	-	-
	Basement Insulation Impact	-	-
	Attic Insulation Impact	-	-
CZ5	Whole Home Insulation Impact	100%	100%
	Wall Insulation Impact	53%[17]	53%
	Basement Insulation Impact	12%	12%
	Attic Insulation Impact	39%	39%

Table 33 to Table 35 show the impact of different insulation scenarios on the total site energy consumption and savings. Comparing R0 (no insulation) to R4 (full home insulation), it is seen that full envelope insulation results in a drop in the total site energy consumption by 52% and 68% for CZ3 and CZ5, respectively. The savings from the case with full home insulation in CZ5 is around 3.6 times that in CZ3, owing to the dominance of space heating energy consumption in CZ5.

[17] Fuel Oil Gas Savings% (Wall Insulation Impact) $= \frac{\text{Fuel Oil Savings (Wall Insulation)}}{\text{Fuel Oil Savings (Whole Home Insulation)}}\%$

Table 33: Total Site Energy Consumption by End Use, Climate Zone and Insulation Scenario for the Case with Current Heating Systems Mix (Residential Prototype)

CZ	Scenario	Total Site Energy Use [kBtu]
CZ3	R0 – No Insulation	138,104
	R1 – Basement + Attic Insulation (No Wall Insulation)	105,839
	R2 – Wall + Attic Insulation (No Basement insulation)	72,676
	R3 – Wall + Basement Insulation (No Attic Insulation)	93,563
	R4 – Fully Insulated Home (Whole Home Insulation)	66,636
CZ5	R0 – No Insulation	378,844
	R1 – Basement + Attic Insulation (No Wall Insulation)	258,884
	R2 – Wall + Attic Insulation (No Basement insulation)	151,138
	R3 – Wall + Basement Insulation (No Attic Insulation)	221,618
	R4 – Fully Insulated Home (Whole Home Insulation)	121,197

Table 34: Impact of Insulation on Total Site Energy Savings by End Use and Climate Zone for the Case with Current Heating Systems Mix (Residential Prototype)

CZ	Scenario	Total Site Energy Savings [kBtu]
CZ3	Whole Home Insulation Impact	71,468[18]
	Wall Insulation Impact	39,203
	Basement Insulation Impact	6,040
	Attic Insulation Impact	26,927
CZ5	Whole Home Insulation Impact	257,647
	Wall Insulation Impact	137,697
	Basement Insulation Impact	29,940
	Attic Insulation Impact	100,420

Table 35: Total Site Energy Percent Savings by End Use, Climate Zone and Insulation Scenario for the Case with Current Heating Systems Mix (Residential Prototype)

CZ	Scenario	Total Site Energy Savings [%]
CZ3	Whole Home Insulation Impact	100%
	Wall Insulation Impact	55%[19]
	Basement Insulation Impact	8%
	Attic Insulation Impact	38%
CZ5	Whole Home Insulation Impact	100%
	Wall Insulation Impact	53%
	Basement Insulation Impact	12%
	Attic Insulation Impact	39%

[18] Total Site Energy Savings (Whole Home Insulation Impact) = R0 (No Insulation) Total Site Energy Consumption - R4 (Whole Home Insulation) Total Site Energy Consumption

[19] $\text{Total Site Energy Savings\% (Wall Insulation Impact)} = \frac{\text{Total Site Energy Savings (Wall Insulation)}}{\text{Total Site Energy Savings (Whole Home Insulation)}}\%$

4.1.1.2 Scenario 2: 100% Heat Pump Systems

This scenario explores a hypothesized future where all single-family homes with fossil-fuel heating systems transition to heat pumps. As such, Table 36 to

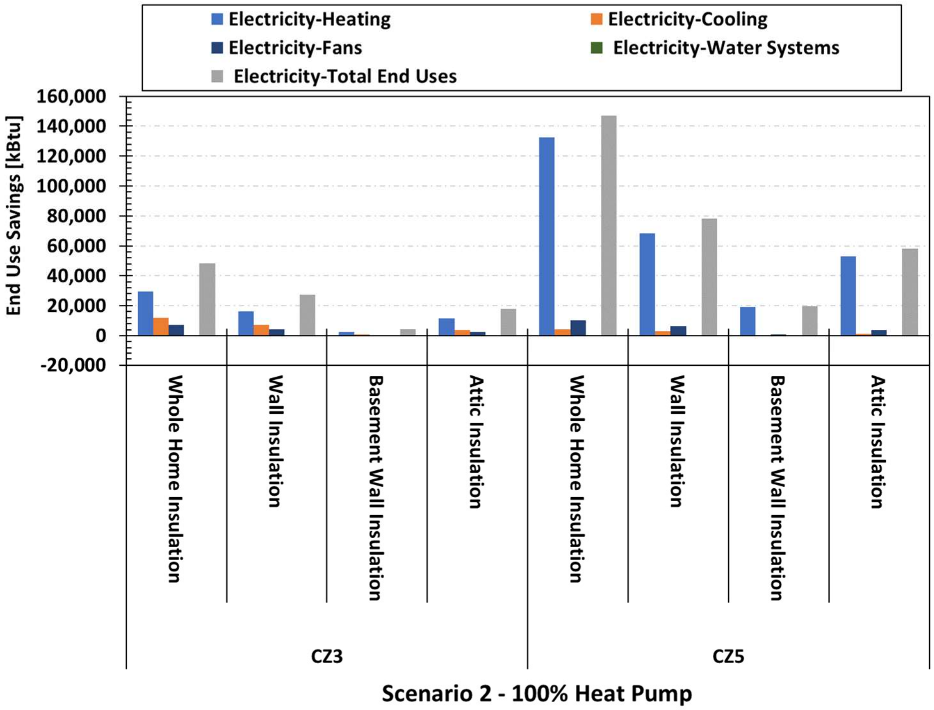

Figure 8: Impact of Insulation on Electricity End Use Savings for the Case with 100% Heat Pump Systems

Table 38, and Figure 7 and Figure 8 demonstrate the electricity end use consumption and savings for a prototypical single-family detached home with only heat pump systems providing space heating and cooling and hot water demands.

Comparing both scenarios, one key observation here is that the average home in CZ5 enjoys higher energy savings from the transition to 100% heat pump systems compared to that in CZ3 due to the higher penetration of heat pumps currently in CZ3 (~70% of homes) compared to CZ5 (~21% of homes). Otherwise, similar trends can be noticed in this scenario.

Table 36: Electricity Consumption by End Use, Climate Zone and Insulation Scenario for the 100% Heat Pump Case (Residential Prototype)

CZ	Scenario	Electricity Consumption [kBtu]					
		Heating	Cooling	Fans	Water Systems	Other	Total End Uses
CZ3	R0 – No Insulation	38,448	18,569	10,292	3,128	35,976	106,413
	R1 – Basement + Attic Insulation (No Wall Insulation)	25,149	13,691	7,316	3,123	35,976	85,255
	R2 – Wall + Attic Insulation (No Basement insulation)	11,634	7,547	3,792	3,116	35,976	62,066
	R3 – Wall + Basement Insulation (No Attic Insulation)	20,551	10,610	5,777	3,119	35,976	76,033
	R4 – Fully Insulated Home (Whole Home Insulation)	9,011	6,659	3,224	3,113	35,976	57,983

CZ5	R0 – No Insulation	168,761	7,034	14,519	4,471	38,854	233,638
	R1 – Basement + Attic Insulation (No Wall Insulation)	104,728	5,863	10,839	4,463	38,854	164,748
	R2 – Wall + Attic Insulation (No Basement insulation)	55,229	2,643	4,966	4,452	38,854	106,143
	R3 – Wall + Basement Insulation (No Attic Insulation)	88,969	4,260	8,134	4,459	38,854	144,677
	R4 – Fully Insulated Home (Whole Home Insulation)	36,207	2,856	4,366	4,449	38,854	86,732

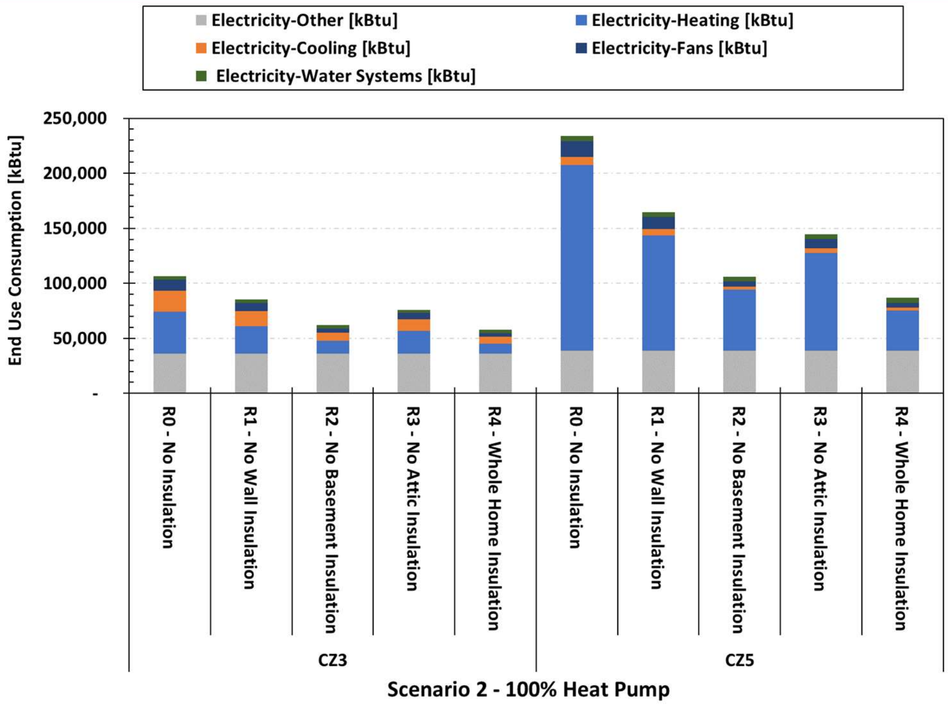

Figure 7: Electricity End Use Consumption for the Case with 100% Heat Pump Systems

Table 37: Impact of Insulation on Electricity Savings by End Use and Climate Zone for the Case with 100% Heat Pump (Residential Prototype)

CZ	Scenario	Electricity Savings [kBtu]				
		Heating	Cooling	Fans	Water Systems	Total End Uses
CZ3	Whole Home Insulation Impact	29,437[20]	11,910	7,067	16	48,430
	Wall Insulation Impact	16,138	7,032	4,092	10	27,271
	Basement Insulation Impact	2,623	888	568	3	4,082
	Attic Insulation Impact	11,540	3,951	2,552	6	18,049
CZ5	Whole Home Insulation Impact	132,554	4,178	10,153	22	146,906
	Wall Insulation Impact	68,520	3,007	6,474	14	78,015

[20] Electricity Savings (Whole Home Insulation Impact) = R0 (No Insulation) Electricity Consumption – R4 (Whole Home Insulation) Electricity Consumption

	Basement Insulation Impact	19,021	-213	600	2	19,410
	Attic Insulation Impact	52,762	1,404	3,768	10	57,945

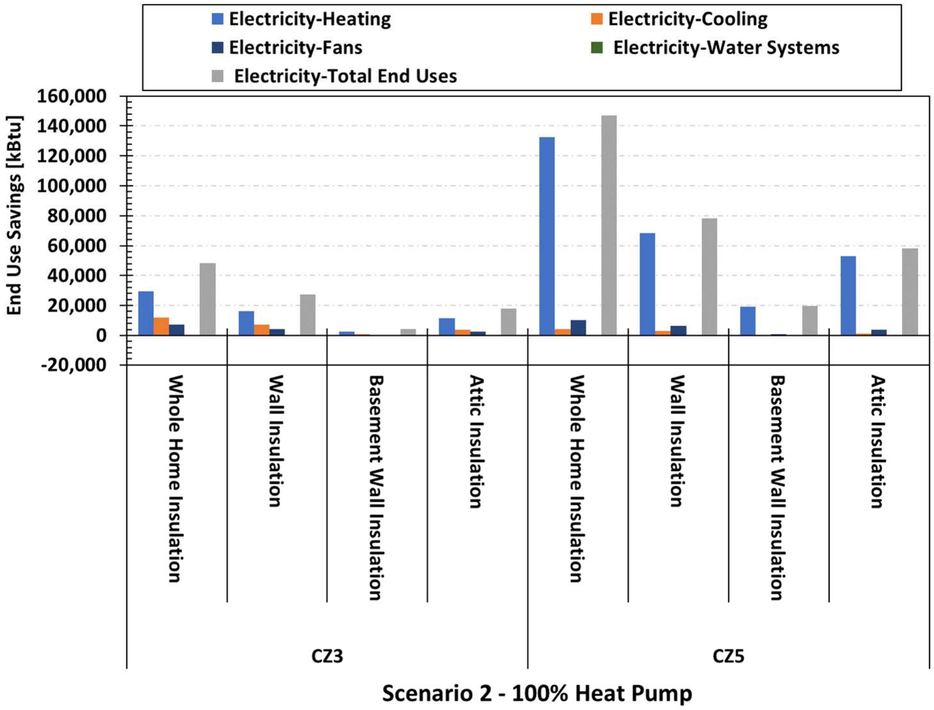

Figure 8: Impact of Insulation on Electricity End Use Savings for the Case with 100% Heat Pump Systems

Table 38: Electricity Percent Savings by End Use, Climate Zone and Insulation Scenario for the Case with 100% Heat Pump (Residential Prototype)

CZ	Scenario	Electricity Savings [%]				
		Heating	Cooling	Fans	Water Systems	Total End Uses
CZ3	Whole Home Insulation Impact	100%	100%	100%	100%	100%
	Wall Insulation Impact	55%[21]	59%	58%	63%	56%
	Basement Insulation Impact	9%	7%	8%	21%	8%
	Attic Insulation Impact	39%	33%	36%	39%	37%
CZ5	Whole Home Insulation Impact	100%	100%	100%	100%	100%
	Wall Insulation Impact	52%	72%	64%	66%	53%
	Basement Insulation Impact	14%	-5%	6%	11%	13%
	Attic Insulation Impact	40%	34%	37%	48%	39%

4.1.2 GHG Accounting

This section extends the analysis to explore the effect of insulating different elements of the home's envelope on GHG emissions.

[21] $\text{Electricity Savings\% (Wall Insulation Impact)} = \frac{\text{Electricity Savings (Wall Insulation)}}{\text{Electricity Savings (Whole Home Insulation)}}\%$

Table 39 and Table 40 present the insulation characteristics of the different envelope elements and the total embodied carbon in each for CZ3 and CZ5, respectively.

Table 39: Insulation Characteristics for Different Envelope Elements and Total Embodied Carbon for CZ3 (Residential Prototype)

Envelope Element	Insulation Layer	Material	Area [ft^2]	Framing Factor [%]	Embodied Carbon [metric tonne]
Exterior Wall	Continuous	50/50 XPS/EPS	2,041.59	0%	0.786
Exterior Wall	Cavity	50/50 cc-SPF/oc-SPF	2,041.59	25%	0.959
Basement Wall	Continuous	XPS	1,115.00	0%	0.514
Attic Roof	Cavity	cc-SPF	1,229.98	10%	1.74
Attic Roof	Continuous	cc-SPF	1,229.98	10%	1.74
Attic Gable End Wall	Continuous	50/50 XPS/EPS	118.70	0%	0.046
Attic Gable End Wall	Cavity	50/50 cc-SPF/oc-SPF	118.70	22%	0.058

Table 40: Insulation Characteristics for Different Envelope Elements and Total Embodied Carbon for CZ5 (Residential Prototype)

Envelope Element	Insulation Layer	Material	Area [ft^2]	Framing Factor [%]	Embodied Carbon [metric tonne]
Exterior Wall	Continuous	50/50 XPS/EPS	2,041.59	0%	1.57
Exterior Wall	Cavity	50/50 cc-SPF/oc-SPF	2,041.59	25%	0.959
Basement Wall	Continuous	XPS	1,115.00	0%	1.03
Basement Wall	Continuous	50/50 XPS/EPS	1,115.00	0%	0.429
Attic Roof	Cavity	cc-SPF	1,229.98	10%	1.74
Attic Roof	Continuous	cc-SPF	1,229.98	10%	2.22
Attic Gable End Wall	Continuous	50/50 XPS/EPS	118.70	0%	0.091
Attic Gable End Wall	Cavity	50/50 cc-SPF/oc-SPF	118.70	22%	0.058

Table 41 shows the total embodied carbon in each insulation scenario for CZ3 and CZ5.

Table 41: Total Embodied Carbon for Different Envelope Elements Insulation for CZ3 and CZ5 (Residential Prototype)

Scenario	Embodied Carbon [metric tonne]	
	CZ3	CZ5
Wall Insulation	1.74	2.53
Basement Insulation	0.514	1.46

Attic Insulation	3.13	4.11
Whole Home Insulation	5.39	8.09

Table 42 demonstrates the source energy savings for Scenario 1, calculated using the site energy savings impact (Table 34) and the source-site ratios displayed (Table 19).

Table 42: Source Energy Savings for Different Fuel Types in Scenario 1: Current Heating Systems Mix (Residential Prototype)

Scenario	Source Electricity Savings [kBtu]		Source Natural Gas Savings [kBtu]		Source Fuel Oil Savings [kBtu]	
	CZ3	CZ5	CZ3	CZ5	CZ3	CZ5
Wall Insulation Impact	68,517	74,272	17,415	117,722	-	4,958
Basement insulation Impact	10,035	13,540	2,876	26,519	-	1,123
Attic Insulation Impact	44,917	51,802	12,754	86,654	-	3,697
Whole Home Insulation Impact	121,576	133,477	32,979	222,242	-	9,360

Table 43 shows that the carbon payback period for all insulation scenarios is under a year. Shorter payback periods are observed in CZ5, despite the higher embodied carbon, due to the much larger first year GHG savings relative to CZ3.

Table 44 and Table 45 demonstrate the lifetime carbon savings and the carbon avoidance ratio (i.e., lifetime savings to embodied carbon ratio), respectively. It is seen that for the whole home insulation case the carbon avoidance ratio is in the range of 50-171 for CZ3 and 134-222 for CZ5, depending on the three Cambium predictions for future contribution of renewable electricity generation. See section 3.5 for further information regarding the Cambium High-, Meduim-, Low-Renewable Energy (RE) Cost of conversion.

Table 43: Carbon Payback Period Using Different Electricity Emission Rates for Scenario 1: Current Heating Systems Mix (Residential Prototype)

Scenario	Carbon Payback Period [months]					
	CZ3			CZ5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	2.8	3.0	3.5	2.2	2.3	2.5
Basement insulation Impact	5.5	5.9	6.8	6.3	6.5	7.0
Attic Insulation Impact	7.5	8.1	9.3	5.0	5.2	5.6
Whole Home Insulation Impact	4.8	5.2	6.0	3.8	4.0	4.3

Table 44: Lifetime Carbon Savings Using Different Electricity Emission Rates for Scenario 1: Current Heating Systems Mix (Residential Prototype)

Scenario	Lifetime Carbon Savings [metric tonne]					
	CZ3			CZ5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	514	198	147	977	635	579
Basement insulation Impact	77	30	23	199	137	127
Attic Insulation Impact	342	135	101	701	462	423
Whole Home Insulation Impact	920	360	268	1,800	1,185	1,085

Table 45: Carbon Avoidance Ratio Using Different Electricity Emission Rates for Scenario 1: Current Heating Systems Mix (Residential Prototype)

Scenario	Carbon Avoidance Ratio [-]					
	CZ3			CZ5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	295	114	84	386	251	229
Basement insulation Impact	149	59	44	137	94	87
Attic Insulation Impact	109	43	32	171	112	103
Whole Home Insulation Impact	171	67	50	222	146	134

Table 46 demonstrates the source energy savings for Scenario 2 (total electrification to HP cooling and heating), calculated using the site energy savings impact (Table 37) in the previous sections and the source-site ratios displayed in Table 19. Similar to Scenario 1,

Table 47 shows that the carbon payback period for all insulation scenarios is less than a year.

Table 48 and Table 49 demonstrate the lifetime carbon savings and the carbon avoidance ratio, respectively. It is seen that for the whole home insulation case the carbon avoidance ratio ranges between 30-172 for CZ3 and 60-348 for CZ5, depending on the three Cambium cases for the rate of future replacement of fossil electricity generation by renewable electricity generation. It is worth mentioning that the transition of the heating systems from fossil fuel to heat pumps (even at federal minimum efficiency levels) is expected to reduce the total energy consumption of the home regardless of amount of insulation provided. As a result, the total modeled energy savings from insulating the envelope decreases as expected, but with the benefit of allowing for a smaller sized heat pump. Thus, it is seen that both equipment efficiency and envelope efficiency have complimentary benefits on reducing energy use and carbon emissions. But, taken in combination with the lower emission rate of electricity relative to natural gas and fuel oil, Scenario 2 generally shows smaller (but still well above zero) carbon avoidance ratios compared to Scenario 1. The exception is the CZ5 High RE Cost scenario, due to the high grid emissions rates and larger heating loads.

Table 46: Source Energy Savings for Different Fuel Types in Scenario 2: 100% Heat Pump Systems (Residential Prototype)

Scenario	Source Electricity Savings [kBtu]	
	CZ3	CZ5
Wall Insulation Impact	80,451	230,145
Basement insulation Impact	12,043	57,260
Attic Insulation Impact	53,246	170,938
Whole Home Insulation Impact	142,868	433,373

Table 47: Carbon Payback Period Using Different Electricity Emission Rates for Scenario 2: 100% Heat Pump Systems (Residential Prototype)

Scenario	Carbon Payback Period [months]					
	CZ3			CZ5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	2.7	2.9	3.5	1.4	1.5	1.8
Basement insulation Impact	5.3	5.8	6.8	3.2	3.4	4.1
Attic Insulation Impact	7.4	8.0	9.4	3.0	3.3	3.9
Whole Home Insulation Impact	4.7	5.1	6.1	2.3	2.5	3.0

Table 48: Lifetime Carbon Savings Using Different Electricity Emission Rates for Scenario 2: 100% Heat Pump Systems (Residential Prototype)

Scenario	Lifetime Carbon Savings [metric tonne]					
	CZ3			CZ5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	522	151	91	1,494	433	260

Basement insulation Impact	78	23	14	372	108	65
Attic Insulation Impact	346	100	60	1,110	322	193
Whole Home Insulation Impact	927	269	161	2,813	816	489

Table 49: Carbon Avoidance Ratio Using Different Electricity Emission Rates for Scenario 2: 100% Heat Pump Systems (Residential Prototype)

Scenario	Carbon Avoidance Ratio [-]					
	CZ3			CZ5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	299	87	52	590	171	103
Basement insulation Impact	152	44	26	255	74	44
Attic Insulation Impact	110	32	19	270	78	47
Whole Home Insulation Impact	172	50	30	348	101	60

Appendix A displays figures that demonstrate the embodied carbon and the cumulative GHG savings over 75 years (2024-2098) using high, medium and low Renewable Energy (RE) cost scenarios, respectively, for electricity emission rates.

4.2 Commercial Prototype: Medium Office

4.2.1 Energy Accounting

4.2.1.1 Scenario 1: Natural Gas Heating

This scenario simulates the case where the office building is heated using a natural-gas fired packaged system with electric resistance terminal reheat coils at the thermal zones, and cooled using a DX cooling coil. The water heating is provided by a centralized natural-gas storage-tank water heater.

Table 50 to * **Recall that CZ3 does not require slab insulation**

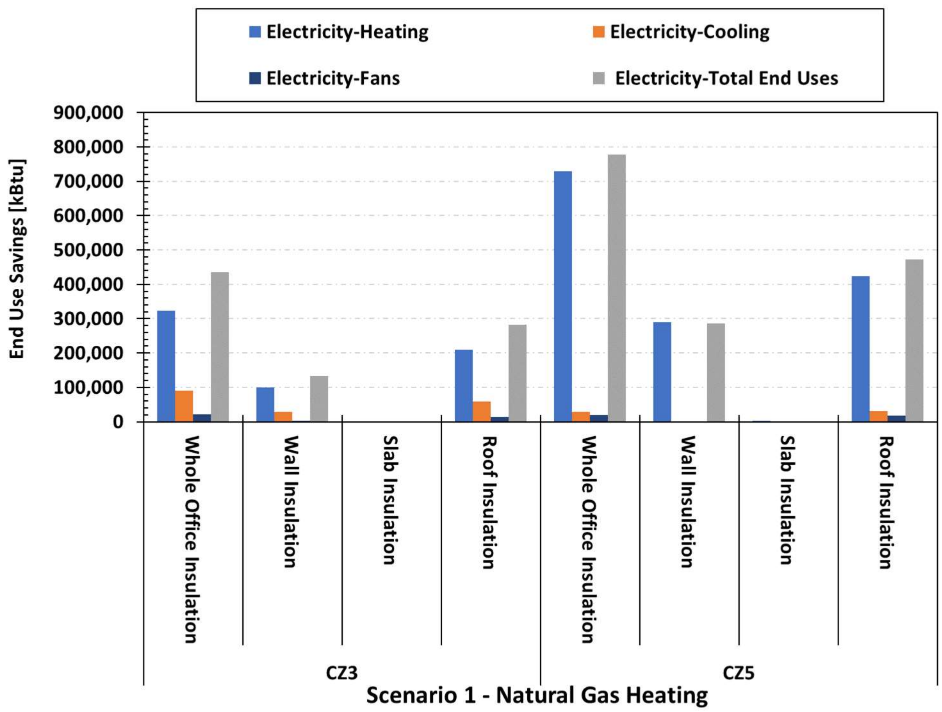

Figure 10: Impact of Insulation on Electricity End Use Percent Savings for Scenario 1 – Natural Gas Heating

Table 52, and Figure 9 and Figure 10 show the effect of insulation scenarios on the electricity end use consumption and savings in CZ3 and CZ5. It is worth mentioning here that CZ 3 does not require slab insulation. As such, scenario C2 was retained only for visual consistency, and its results should match those of scenario C4.

In general, the results from the commercial prototype simulations follow similar trends to those from the residential prototype simulations. However, the magnitudes of energy consumption and savings are multiple times higher for the medium office when compared to a single-family home.

Table 50 shows the electricity consumption for each scenario modeled. Comparing C0 to C4, it is seen that the heating consumption dropped by 93% and 91%, and the cooling consumption dropped by 24% and 18% for CZ3 and CZ5, respectively. Also, the consumption of HVAC system fans dropped by around 24%.

Table 50: Electricity Consumption by End Use, Climate Zone and Insulation Scenario for the Case with Natural Gas Heating (Commercial Prototype)

CZ	Scenario	Electricity Consumption [kBtu]				
		Heating	Cooling	Fans	Other	Total End Uses
CZ3	C0 – No Insulation	346,866	371,996	90,106	1,000,705	1,809,670
	C1 – Roof + Slab Perimeter Insulation (No Wall Insulation)	123,516	311,617	71,225	1,000,705	1,507,064
	C2 – Wall + Roof Insulation (No Slab insulation)	23,683	282,178	68,025	1,000,705	1,374,591
	C3 – Wall + Slab Perimeter Insulation (No Attic Insulation)	232,727	340,712	82,880	1,000,705	1,657,024
	C4 – Fully Insulated Office (Whole Office Insulation)	23,683	282,178	68,025	1,000,705	1,374,591
CZ5	C0 – No Insulation	800,798	160,652	87,566	1,001,836	2,050,849
	C1 – Roof + Slab Perimeter Insulation (No Wall Insulation)	362,057	129,023	65,260	1,001,836	1,558,173
	C2 – Wall + Roof Insulation (No Slab insulation)	75,020	129,712	66,827	1,001,836	1,273,389
	C3 – Wall + Slab Perimeter Insulation (No Attic Insulation)	496,138	161,328	85,142	1,001,836	1,744,445
	C4 – Fully Insulated Office (Whole Office Insulation)	71,996	131,039	68,094	1,001,836	1,272,959

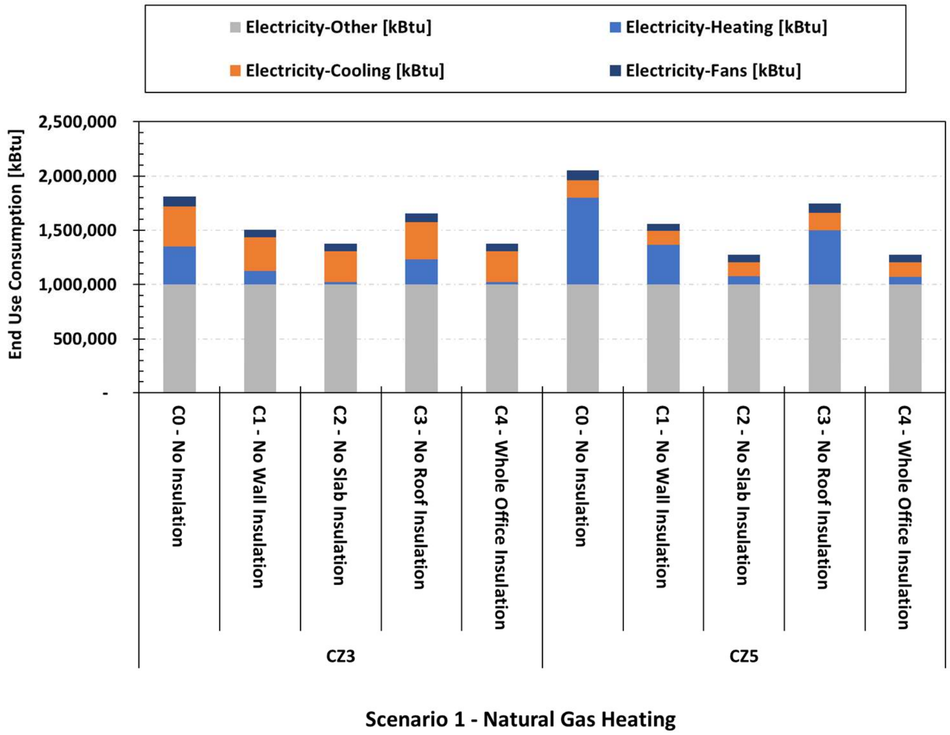

Figure 9: Electricity End Use Consumption for Scenario 1 – Natural Gas Heating

Comparing CZ3 to CZ5, the latter exhibits higher heating consumption and lower cooling consumption due to the cooler climate, yielding a net positive increase in total electricity consumption. This also results in larger savings in heating consumption and lower savings in cooling consumption in CZ5 relative to CZ3, shown Table 51 and Figure 10. One interesting observation on cooling electricity consumption and savings in CZ5 was that the scenarios with partial insulation (C1 and C2) showed lower consumption and larger savings than the scenario with full building insulation (C4). Also, scenario C3 (no roof insulation) exhibited larger cooling consumption than scenario C0 (no insulation), indicating negative savings in cooling electricity use. Such behavior was verified and is likely attributed to the free cooling imparted by the cooler outdoor temperatures during summer in CZ5. The fan consumption was noticed to follow the same trend as the cooling consumption rather than heating because most of the heating load is supplied by the terminal reheat coils right at the thermal zones, thereby having lesser influence on fan consumption.

Table 51, * **Recall that CZ3 does not require slab insulation**

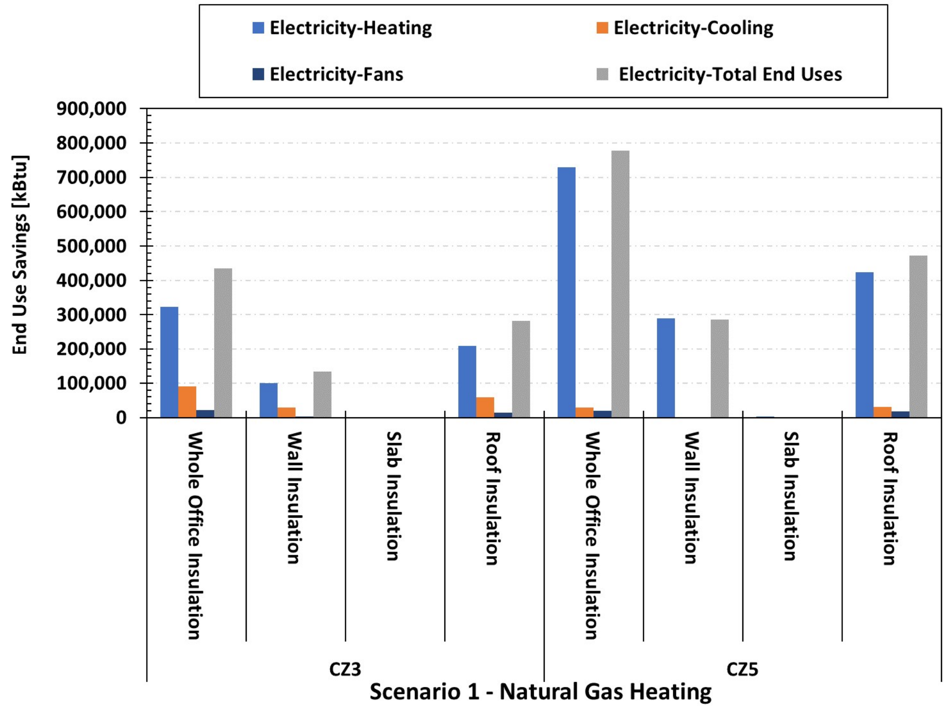

Figure 10: Impact of Insulation on Electricity End Use Percent Savings for Scenario 1 – Natural Gas Heating

Table 52 and Figure 10 show that the roof insulation has the largest impact on the savings, followed by the exterior wall insulation, then the slab perimeter insulation. This observation aligns with expectations since the roof area is around 1.25 times that of the exterior opaque wall area.

Table 51: Impact of Insulation on Electricity Savings by End Use and Climate Zone for the Case with Natural Gas Heating (Commercial Prototype)

CZ	Scenario	Electricity Savings [kBtu]			
		Heating	Cooling	Fans	Total End Uses
CZ3	Whole Office Insulation Impact	323,183[22]	89,818	22,081	435,080
	Wall Insulation Impact	99,834	29,439	3,200	132,473
	Slab Perimeter Insulation Impact*	-	-	-	-
	Roof Insulation Impact	209,044	58,534	14,855	282,434
CZ5	Whole Office Insulation Impact	728,802	29,613	19,471	777,889

[22] Electricity Savings (Whole Office Insulation Impact) = C0 (No Insulation) Electricity Consumption - C4 (Whole Office Insulation) Electricity Consumption

	Wall Insulation Impact	290,060	-2,016	-2,834	285,214
	Slab Perimeter Insulation Impact	3,024	-1,327	-1,267	430
	Roof Insulation Impact	424,142	30,289	17,048	471,485

* Recall that CZ3 does not require slab insulation

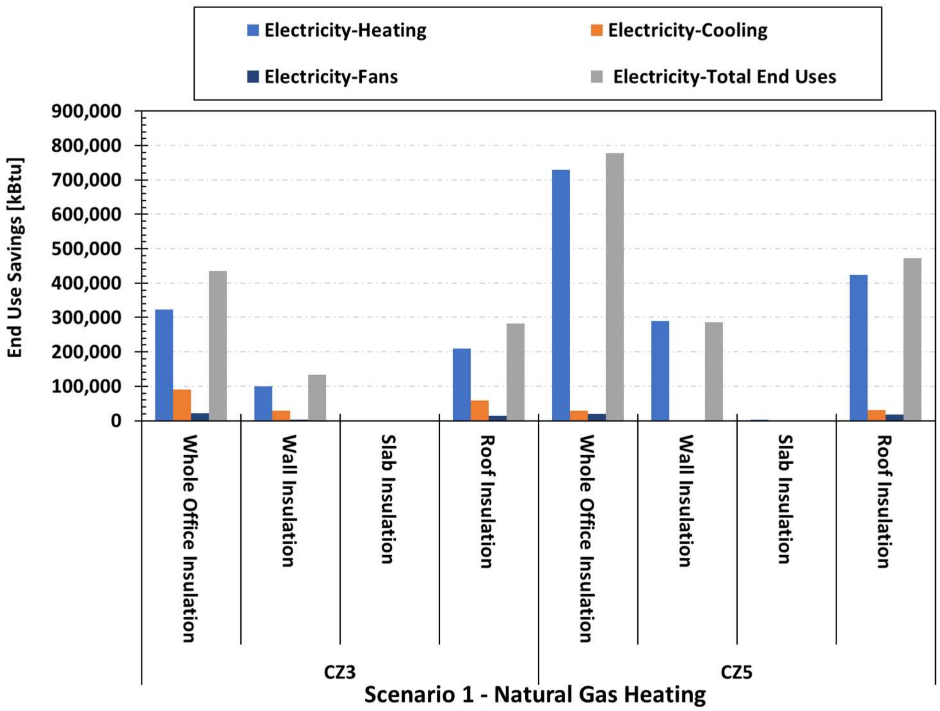

Figure 10: Impact of Insulation on Electricity End Use Percent Savings for Scenario 1 – Natural Gas Heating

Table 52: Electricity Percent Savings by End Use, Climate Zone and Insulation Scenario for the Case with Natural Gas Heating (Commercial Prototype)

CZ	Scenario	Electricity Savings [%]			
		Heating	Cooling	Fans	Total End Uses
CZ3	Whole Office Insulation Impact	100%	100%	100%	100%
	Wall Insulation Impact	31%[23]	33%	14%	30%
	Slab Perimeter Insulation Impact	0%	0%	0%	0%
	Roof Insulation Impact	65%	65%	67%	65%
CZ5	Whole Office Insulation Impact	100%	100%	100%	100%
	Wall Insulation Impact	40%	-7%	-15%	37%

[23] $\text{Electricity Savings\% (Wall Insulation Impact)} = \frac{\text{Electricity Savings (Wall Insulation)}}{\text{Electricity Savings (Whole Office Insulation)}}\%$

	Slab Perimeter Insulation Impact	0%	-4%	-7%	0%
	Roof Insulation Impact	58%	102%	88%	61%

Table 53 to

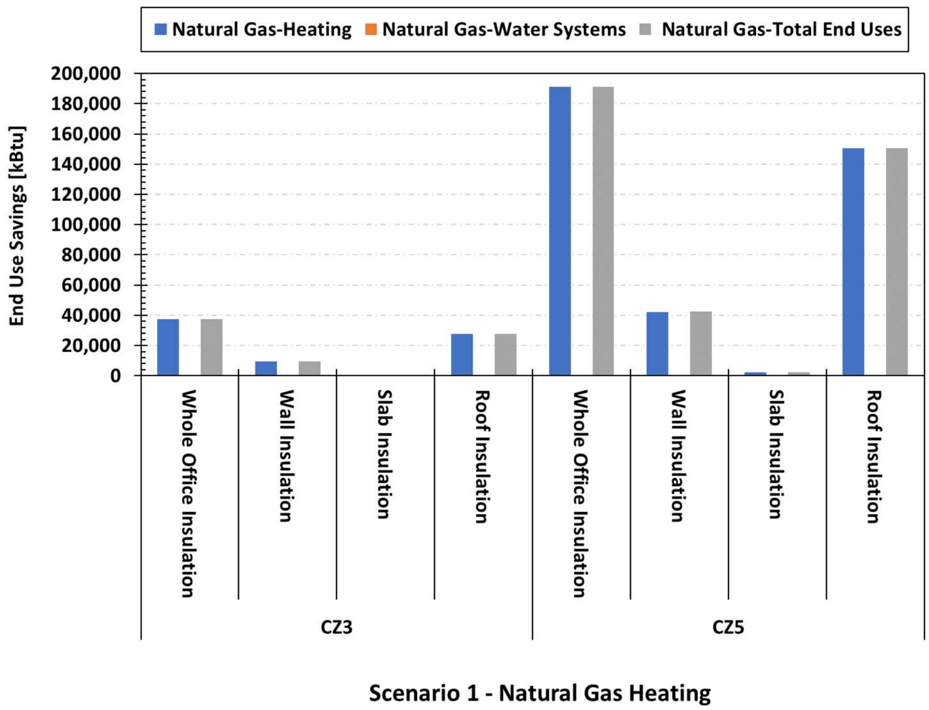

Figure 12: Impact of Insulation on Natural Gas End Use Savings for Scenario 1 – Natural Gas Heating

Table 55, and Figure 11 and Figure 12 demonstrate the impact of insulation scenarios on natural gas end use consumption and savings. It is important to note here that the natural gas heating coil only provides a portion of the heating load; 12-42% for scenarios C0 (no insulation) to C4 (full insulation) in CZ3 and 26%-64% for scenarios C0 to C4 in CZ5. The remainder of the heating load is covered by electric resistance terminal reheat coils. The results generally show similar trends to those observed in electricity heating consumption and savings. It is also seen that the natural gas savings in water heating system increased with increasing the level of envelope insulation (i.e., going from C0 to C4). This is likely attributed to the reduction of thermal losses in winter from hot water pipes extended to uninsulated spaces. However, the percent savings in water heating systems point to the dominant effect of exterior wall insulation, contrary to space heating whose savings are dominated by the effect of the roof insulation. This is likely attributed to the fact that approximately one third of the hot water piping is expected to exist on the third floor of the office building. This is why the thermal losses from the hot water piping will be primarily driven by the exterior wall insulation.

Table 53: Natural Gas Consumption by End Use, Climate Zone and Insulation Scenario for the Case with Natural Gas Heating (Commercial Prototype)

CZ	Scenario	Natural Gas Consumption [kBtu]		
		Heating	Water Systems	Total End Uses
CZ3	C0 – No Insulation	58,847	73,778	132,625
	C1 – Roof + Slab Perimeter Insulation (No Wall Insulation)	31,009	73,762	104,775
	C2 – Wall + Roof Insulation (No Slab insulation)	21,474	73,718	95,192
	C3 – Wall + Slab Perimeter Insulation (No Attic Insulation)	49,012	73,737	122,745
	C4 – Fully Insulated Office (Whole Office Insulation)	21,474	73,718	95,192
CZ5	C0 – No Insulation	347,748	83,007	430,751
	C1 – Roof + Slab Perimeter Insulation (No Wall Insulation)	198,849	82,991	281,840
	C2 – Wall + Roof Insulation (No Slab insulation)	158,747	82,880	241,627
	C3 – Wall + Slab Perimeter Insulation (No Attic Insulation)	307,194	82,893	390,087
	C4 – Fully Insulated Office (Whole Office Insulation)	156,583	82,877	239,463

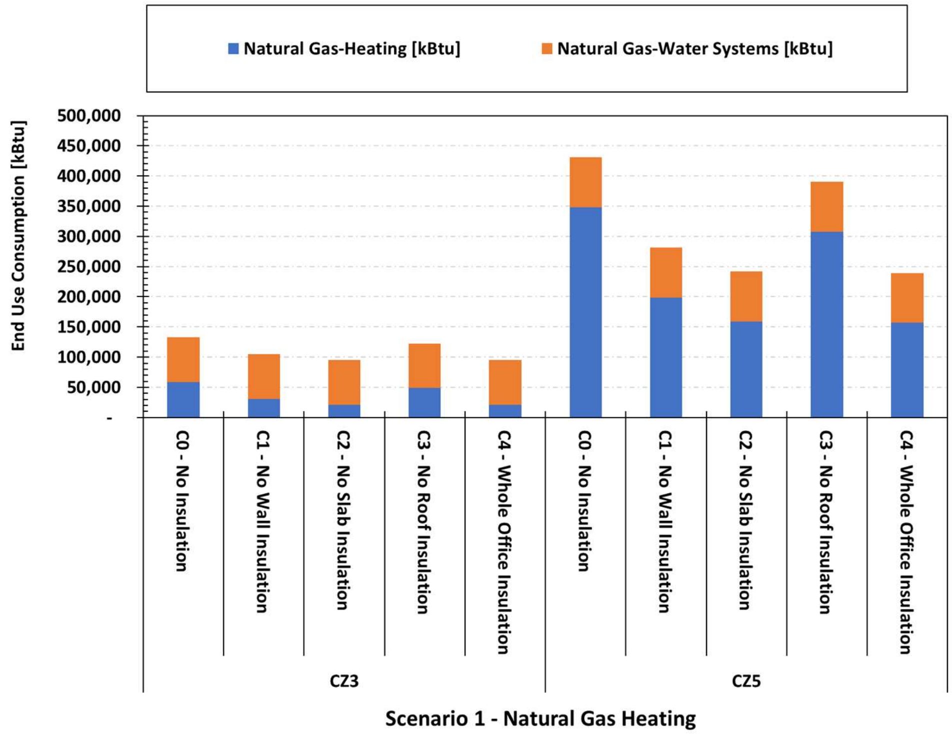

Figure 11: Natural Gas End Consumption for Scenario 1 – Natural Gas Heating

Table 54: Impact of Insulation on Natural Gas Savings by End Use and Climate Zone for the Case with Natural Gas Heating (Commercial Prototype)

CZ	Scenario	Natural Gas Savings		
		Heating	Water Systems	Total End Uses
CZ3	Whole Office Insulation Impact	37,372[24]	60	37,432
	Wall Insulation Impact	9,535	44	9,582
	Slab Perimeter Insulation Impact	-	-	-
	Roof Insulation Impact	27,537	19	27,553

[24] Natural Gas Savings (Whole Office Insulation Impact) = C0 (No Insulation) Natural Gas Consumption - C4 (Whole Office Insulation) Natural Gas Consumption

CZ5	Whole Office Insulation Impact	191,165	130	191,288
	Wall Insulation Impact	42,266	114	42,377
	Slab Perimeter Insulation Impact	2,164	3	2,164
	Roof Insulation Impact	150,611	16	150,624

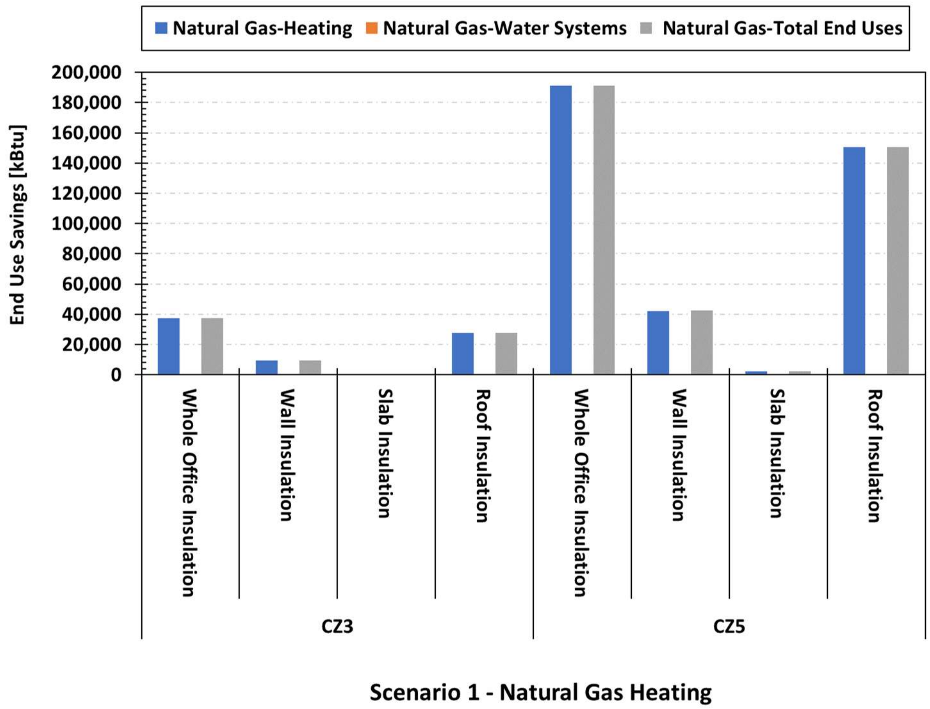

Figure 12: Impact of Insulation on Natural Gas End Use Savings for Scenario 1 – Natural Gas Heating

Table 55: Natural Gas Percent Savings by End Use, Climate Zone and Insulation Scenario for the Case with Natural Gas Heating (Commercial Prototype)

CZ	Scenario	Natural Gas Savings [%]		
		Heating	Water Systems	Total End Uses
CZ3	Whole Office Insulation Impact	100%	100%	100%
	Wall Insulation Impact	26%[25]	74%	26%
	Slab Perimeter Insulation Impact	0%	0%	0%
	Roof Insulation Impact	74%	32%	74%
CZ5	Whole Office Insulation Impact	100%	100%	100%

[25] $\text{Natural Gas Savings\% (Wall Insulation Impact)} = \frac{\text{Natural Gas Savings (Wall Insulation)}}{\text{Natural Gas Savings (Whole Office Insulation)}}\%$

	Wall Insulation Impact	22%	88%	22%
	Slab Perimeter Insulation Impact	1%	2%	1%
	Roof Insulation Impact	79%	12%	79%

Table 56 to Table 58 present the aggregate effect of the different insulation scenarios on the total site energy consumption and savings. One key observation is that the impact of slab perimeter insulation in CZ5 has a negligible effect. This may be attributed to the fact that the heating and cooling load on the first floor are dominated by the heat transfer through the exterior walls rather than the thermal bridging effect of the slab. Besides, the soil surrounding the slab perimeter presents a natural thermal resistance to heat transfer through the thickness of the slab. Also, given the size of the commercial building footprint and slab area, placing insulation only at the perimeter has a lesser impact on energy use than if the entire under-slab area were insulated (e.g., fully insulated slab). This slab area to perimeter length ratio effect is not represented in the F-factor approach (which assumes a fixed slab area to perimeter ratio of 9:1)[26]. Therefore, fully insulating the slab would tend to provide greater energy savings but also with an increase in the embodied carbon of the slab insulation, particularly if the F-factor were corrected to account for the actual slab area to perimeter ratio.

Table 56: Total Energy Consumption by End Use, Climate Zone and Insulation Scenario for the Case with Natural Gas Heating (Commercial Prototype)

CZ	Scenario	Total Site Energy Use [kBtu]
CZ3	**C0 – No Insulation**	1,942,295
	C1 – Roof + Slab Perimeter Insulation (No Wall Insulation)	1,611,839
	C2 – Wall + Roof Insulation (No Slab insulation)	1,469,783
	C3 – Wall + Slab Perimeter Insulation (No Attic Insulation)	1,779,770
	C4 – Fully Insulated Office (Whole Office Insulation)	1,469,783
CZ5	**C0 – No Insulation**	2,481,600
	C1 – Roof + Slab Perimeter Insulation (No Wall Insulation)	1,840,013
	C2 – Wall + Roof Insulation (No Slab insulation)	1,515,016
	C3 – Wall + Slab Perimeter Insulation (No Attic Insulation)	2,134,531
	C4 – Fully Insulated Office (Whole Office Insulation)	1,512,422

[26] Davis, Bob, David Baylon, and Mike Kennedy. Super Good Cents Heat Loss Reference: Manufactured Homes: Heat Loss Assumptions and Calculations, Heat Loss Coefficient Tables. No. DOE/BP-35738-3. Ecotope, Inc., Seattle, WA (USA), 1991.

Table 57: Impact of Insulation on Total Site Energy Savings by End Use and Climate Zone for the Case with Natural Gas Heating (Commercial Prototype)

CZ	Scenario	Total Site Energy Savings [kBtu]
CZ3	Whole Office Insulation Impact	472,512[27]
	Wall Insulation Impact	142,056
	Slab Perimeter Insulation Impact	-
	Roof Insulation Impact	309,987
CZ5	Whole Office Insulation Impact	969,178
	Wall Insulation Impact	327,591
	Slab Perimeter Insulation Impact	2,594
	Roof Insulation Impact	622,109

Table 58: Total Energy Percent Savings by End Use, Climate Zone and Insulation Scenario for the Case with Natural Gas Heating (Commercial Prototype)

CZ	Scenario	Total Site Energy Savings [%]
CZ3	Whole Office Insulation Impact	100%
	Wall Insulation Impact	30%[28]
	Slab Perimeter Insulation Impact	-
	Roof Insulation Impact	66%
CZ5	Whole Office Insulation Impact	100%
	Wall Insulation Impact	34%
	Slab Perimeter Insulation Impact	0.3%
	Roof Insulation Impact	64%

4.2.1.2 Scenario 2: 100% Heat Pump Systems

This scenario explores a hypothesized future where all medium office 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

[27] Total Site Energy Savings (Whole Office Insulation Impact) = C0 (No Insulation) Total Site Energy Consumption - C4 (Whole Office Insulation) Total Site Energy Consumption

[28] $\text{Total Site Energy Savings\% (Wall Insulation Impact)} = \frac{\text{Total Site Energy Savings (Wall Insulation)}}{\text{Total Site Energy Savings (Whole Office Insulation)}}\%$

a seasonal average COP of 3.3 for CZ3 and 2.25 for CZ5[29]. Also, the electricity consumption of a heat pump for water heating was estimated using an average COP of 3.3. Table 59 to * Negative **savings primarily due to the fact that insulation is only applied to the perimeter of the slab which presents inherent limitations on the F-factor method assumptions.**

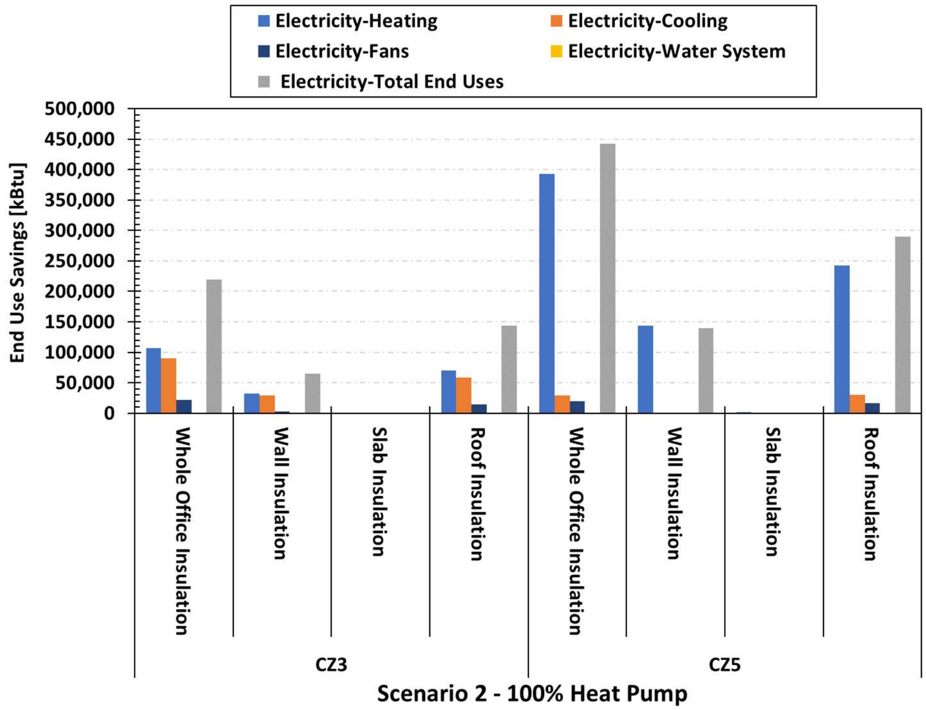

Figure 14: Impact of Insulation on Electricity End Use Percent Savings for the Case with 100% Heat Pump Systems (Commercial Prototype)

Table 61, and Figure 13 and Figure 14 demonstrate the electricity end use consumption and savings for a prototypical medium office building with only heat pump systems providing space heating and cooling and hot water demands. It is seen that the average office generally exhibits lower electricity consumption due to the transition to 100% heat pump systems. Otherwise, the trends are very similar to those in Scenario 1.

Table 59: Electricity Consumption by End Use, Climate Zone and Insulation Scenario for the Case with 100% Heat Pump (Commercial Prototype)

CZ	Scenario	Electricity Consumption [kBtu]					
		Heating	Cooling	Fans	Water Systems	Other	Total End Uses
CZ3	C0 – No Insulation	119,555	371,996	90,106	18,109	1,000,705	1,600,471

[29] Iowa Energy Efficiency Statewide Technical Reference Manual Version 7.0 (2022)

	C1 – Roof + Slab Perimeter Insulation (No Wall Insulation)	45,041	311,617	71,225	18,105	1,000,705	1,446,693
	C2 – Wall + Roof Insulation (No Slab insulation)	12,448	282,178	68,025	18,094	1,000,705	1,381,450
	C3 – Wall + Slab Perimeter Insulation (No Attic Insulation)	82,553	340,712	82,880	18,099	1,000,705	1,524,950
	C4 – Fully Insulated Office (Whole Office Insulation)	12,448	282,178	68,025	18,094	1,000,705	1,381,450
CZ5	**C0 – No Insulation**	481,099	160,652	87,566	20,374	1,001,836	1,751,527
	C1 – Roof + Slab Perimeter Insulation (No Wall Insulation)	232,500	129,023	65,260	20,370	1,001,836	1,448,990
	C2 – Wall + Roof Insulation (No Slab insulation)	90,491	129,712	66,827	20,343	1,001,836	1,309,210
	C3 – Wall + Slab Perimeter Insulation (No Attic Insulation)	331,096	161,328	85,142	20,346	1,001,836	1,599,749
	C4 – Fully Insulated Office (Whole Office Insulation)	88,368	131,039	68,094	20,343	1,001,836	1,309,680

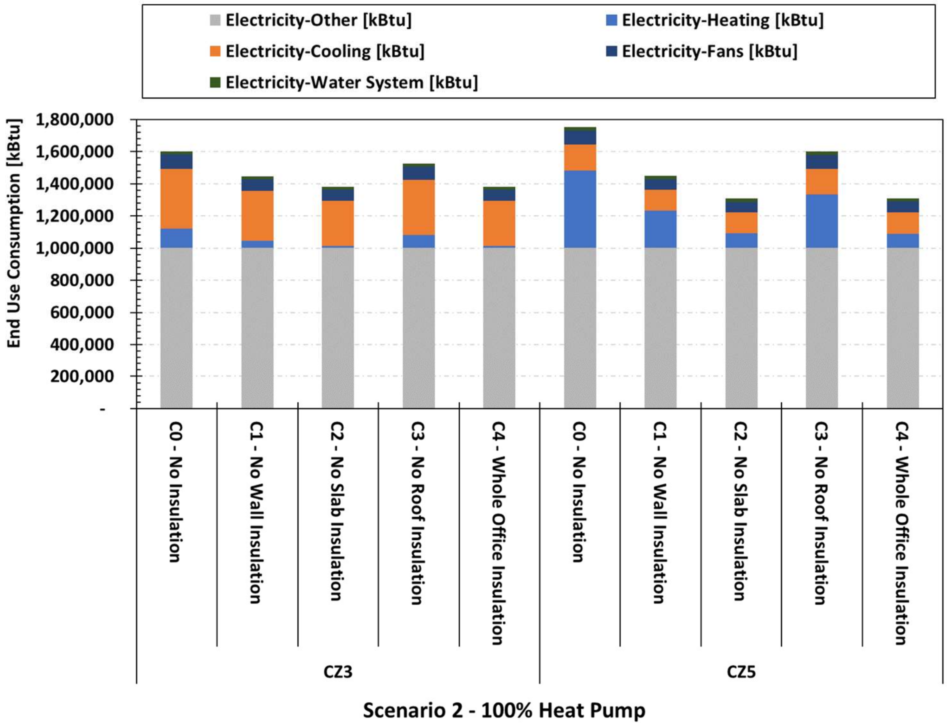

Figure 13: Electricity End Use Consumption for the Case with 100% Heat Pump Systems (Commercial Prototype)

Table 60: Impact of Insulation on Electricity Savings by End Use and Climate Zone for the Case with 100% Heat Pump (Commercial Prototype)

CZ	Scenario	Electricity Savings [kBtu]				
		Heating	Cooling	Fans	Water Systems	Total End Uses
CZ3	Whole Office Insulation Impact	107,108[30]	89,818	22,081	15	219,022
	Wall Insulation Impact	32,593	29,439	3,200	11	65,244
	Slab Perimeter Insulation Impact	-	-	-	-	-
	Roof Insulation Impact	70,106	58,534	14,855	5	143,500
CZ5	Whole Office Insulation Impact	392,731	29,613	19,471	32	441,847
	Wall Insulation Impact	144,132	-2,016	-2,834	28	139,310
	Slab Perimeter Insulation Impact	2,123	-1,327	-267	1	-470*
	Roof Insulation Impact	242,728	30,289	17,048	4	290,069

[30] Electricity Savings (Whole Office Insulation Impact) = C0 (No Insulation) Electricity Consumption - C4 (Whole Office Insulation) Electricity Consumption

*** Negative savings primarily due to the fact that insulation is only applied to the perimeter of the slab which presents inherent limitations on the F-factor method assumptions.**

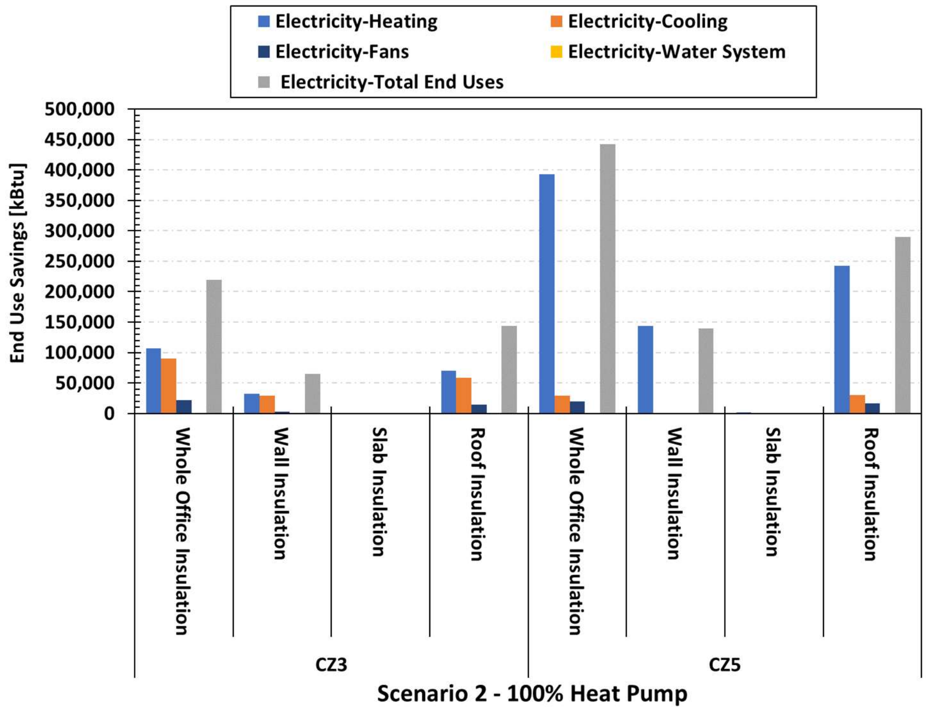

Figure 14: Impact of Insulation on Electricity End Use Percent Savings for the Case with 100% Heat Pump Systems (Commercial Prototype)

Table 61: Electricity Percent Savings by End Use, Climate Zone and Insulation Scenario for the Case with 100% Heat Pump (Commercial Prototype)

CZ	Scenario	Electricity Savings [%]				
		Heating	Cooling	Fans	Water Systems	Total End Uses
CZ3	Whole Office Insulation Impact	100%	100%	100%	100%	100%
	Wall Insulation Impact	30%[31]	33%	14%	74%	30%
	Slab Perimeter Insulation Impact	-	-	-	-	-
	Roof Insulation Impact	65%	65%	67%	32%	66%
CZ5	Whole Office Insulation Impact	100%	100%	100%	100%	100%
	Wall Insulation Impact	37%	-7%	-15%	88%	32%
	Slab Perimeter Insulation Impact	1%	-4%	-7%	2%	-0.1%
	Roof Insulation Impact	62%	102%	88%	12%	66%

[31] $\text{Electricity Savings\% (Wall Insulation Impact)} = \frac{\text{Electricity Savings (Wall Insulation)}}{\text{Electricity Savings (Whole Office Insulation)}}\%$

4.2.2 GHG Accounting

Table 62 and Table 63 present the insulation characteristics of the different envelope elements and the total embodied carbon in each for CZ3 and CZ5, respectively.

Table 62: Insulation Characteristics for Different Envelope Elements and Total Embodied Carbon for CZ3 (Commercial Prototype)

Envelope Element	Insulation Layer	Material	Area [ft²]	Framing Factor [%]	Embodied Carbon [metric tonne]
Exterior Wall	Continuous	Polyiso	14,262.72	0%	4.07
Exterior Wall	Cavity	cc-SPF	14,262.72	10%[32]	8.69
Roof	Continuous	Polyiso	17,875.95	0%	25.3

Table 63: Insulation Characteristics for Different Envelope Elements and Total Embodied Carbon for CZ5 (Commercial Prototype)

Envelope Element	Insulation Layer	Material	Area [ft²]	Framing Factor [%]	Embodied Carbon [metric tonne]
Exterior Wall	Continuous	Polyiso	14,262.72	0%	8.14
Exterior Wall	Cavity	cc-SPF	14,262.72	10%	8.69
Slab Perimeter	Continuous	XPS	1,091.68	0%	1.51
Roof	Continuous	Polyiso	17,875.95	0%	30.4

Table 64 shows the total embodied carbon in each insulation scenario for CZ3 and CZ5. Table 65 demonstrates the source energy savings for Scenario 1, calculated using the site energy savings impact (

Table 57) and the source-site ratios displayed in Table 19.

Table 64: Total Embodied Carbon for Different Envelope Elements Insulation for CZ3 and CZ5 (Commercial Prototype)

Scenario	Embodied Carbon [metric tonne]	
	CZ3	**CZ5**
Wall Insulation	15.6	19.6
Slab Perimeter Insulation	-	1.51
Roof Insulation	25.3	30.4
Whole Office Insulation	40.9	51.5

[32] Assumed the steel framing occupies only 10% of the frame area (i.e., displaces only 10% of the cavity insulation area) available for the spray foam insulation.

Table 65: Source Energy Savings for Different Fuel Types in Scenario 1: Current Heating Systems Mix (Commercial Prototype)

Scenario	Source Electricity Savings [kBtu]		Source Natural Gas Savings [kBtu]	
	CZ3	CZ5	CZ3	CZ5
Wall Insulation Impact	390,796	841,381	10,445	46,191
Slab Perimeter Insulation Impact	–	1,268	–	2,359
Roof Insulation Impact	833,179	1,390,881	30,033	164,180
Whole Office Insulation Impact	1,283,485	2,294,773	40,801	208,504

Table 66 shows that the carbon payback period for all insulation scenarios is less than a year. Shorter payback periods are observed in CZ5, despite the higher embodied carbon, due to the much larger first year GHG savings relative to CZ3. Table 67 and Table 67: Lifetime Carbon Savings Using Different Electricity Emission Rates for Scenario 1: Natural Gas Heating (Commercial Prototype)

Scenario	Lifetime Carbon Savings [metric tonne]					
	CZ3			CZ5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	2,578	777	483	5,645	1,768	1,134
Slab Perimeter Insulation Impact	–	–	–	18	12	11
Roof Insulation Impact	5,528	1,688	1,060	9,681	3,272	2,223
Whole Office Insulation Impact	8,494	2,579	1,611	15,725	5,150	3,420

Table 68 demonstrate the lifetime carbon savings and the carbon avoidance ratio for the whole office insulation case. For the case of whole office insulation, the carbon avoidance ratio was found to be in the range of 39-208 for CZ3 and 66-305 for CZ5, depending on the cost of renewable electricity generation.

Table 66: Carbon Payback Period Using Different Electricity Emission Rates for Scenario 1: Natural Gas Heating (Commercial Prototype)

Scenario	Carbon Payback Period [months]					
	CZ3			CZ5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	4.9	5.3	6.3	2.8	3.1	3.6
Slab Perimeter Insulation Impact	–	–	–	72.5	84.6	93.8
Roof Insulation Impact	3.7	4.0	4.8	2.6	2.8	3.2
Whole Office Insulation Impact	3.9	4.2	5.0	2.7	2.9	3.4

Table 67: Lifetime Carbon Savings Using Different Electricity Emission Rates for Scenario 1: Natural Gas Heating (Commercial Prototype)

Scenario	Lifetime Carbon Savings [metric tonne]					
	CZ3			CZ5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	2,578	777	483	5,645	1,768	1,134
Slab Perimeter Insulation Impact	-	-	-	18	12	11
Roof Insulation Impact	5,528	1,688	1,060	9,681	3,272	2,223
Whole Office Insulation Impact	8,494	2,579	1,611	15,725	5,150	3,420

Table 68: Carbon Avoidance Ratio Using Different Electricity Emission Rates for Scenario 1: Natural Gas Heating (Commercial Prototype)

Scenario	Carbon Avoidance Ratio [-]					
	CZ3			CZ5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	166	50	31	287	90	58
Slab Perimeter Insulation Impact	-	-	-	12	8	7
Roof Insulation Impact	218	67	42	319	108	73
Whole Office Insulation Impact	208	63	39	305	100	66

Table 69 demonstrates the source energy savings for Scenario 2, calculated using the site energy savings impact (

Table 60) and the source-site ratios displayed in Table 19. Similar to Scenario 1, Table 70 shows that the carbon payback period for all insulation scenarios is in the range of 7.5 - 13 months for CZ3, and 4.4 - 7.7 months for CZ5. Table 71 and * Negative **savings primarily due to the fact that insulation is only applied to the perimeter of the slab which presents inherent limitations on the F-factor method modeling assumptions.**

Table 72 display the lifetime carbon savings and the carbon avoidance ratio for the whole office insulation case. It is seen that for the case with whole office insulation the carbon avoidance ratio ranges between 18-103 for CZ3 and 29-164 for CZ5, depending on the cost of renewable electricity generation.

Table 69: Source Energy Savings for Different Fuel Types in Scenario 2: 100% Heat Pump Systems (Commercial Prototype)

Scenario	Source Electricity Savings [kBtu]	
	CZ3	CZ5
Wall Insulation Impact	192,468	410,964

Slab Perimeter Insulation Impact	-	-1,387*
Roof Insulation Impact	423,325	855,702
Whole Office Insulation Impact	646,114	1,303,450

*** Negative savings primarily due to the fact that insulation is only applied to the perimeter of the slab which presents inherent limitations on the F-factor method modeling assumptions.**

Table 70: Carbon Payback Period Using Different Electricity Emission Rates for Scenario 2: 100% Heat Pump Systems (Commercial Prototype)

Scenario	Carbon Payback Period [months]					
	CZ3			CZ5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	10.1	10.9	13.0	6.0	6.5	7.7
Slab Perimeter Insulation Impact	-	-	-	NA*	NA	NA
Roof Insulation Impact	7.5	8.1	9.6	4.4	4.8	5.7
Whole Office Insulation Impact	7.9	8.6	10.2	4.9	5.3	6.3

*** NA indicates that negative savings result in infinite payback period. Recall that negative savings were primarily due to the fact that insulation is only applied to the perimeter of the slab which presents inherent limitations on the F-factor method modeling assumptions.**

Table 71: Lifetime Carbon Savings Using Different Electricity Emission Rates for Scenario 2: 100% Heat Pump Systems (Commercial Prototype)

Scenario	Lifetime Carbon Savings [metric tonne]					
	CZ3			CZ5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	1,249	362	217	2,668	774	464
Slab Perimeter Insulation Impact	-	-	-	-9*	-3	-2
Roof Insulation Impact	2,748	797	478	5,555	1,611	966
Whole Office Insulation Impact	4,194	1,217	730	8,461	2,455	1,472

*** Negative savings primarily due to the fact that insulation is only applied to the perimeter of the slab which presents inherent limitations on the F-factor method modeling assumptions.**

Table 72: Carbon Avoidance Ratio Using Different Electricity Emission Rates for Scenario 2: 100% Heat Pump Systems (Commercial Prototype)

Scenario	Carbon Avoidance Ratio [-]					
	CZ3			CZ5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost

Wall Insulation Impact	80	23	14	136	39	24
Slab Perimeter Insulation Impact	-	-	-	NA*	NA	NA
Roof Insulation Impact	109	32	19	183	53	32
Whole Office Insulation Impact	103	30	18	164	48	29

*** NA indicates that negative savings result in infinite payback period. Recall that negative savings were primarily due to the fact that insulation is only applied to the perimeter of the slab which presents inherent limitations on the F-factor method modeling assumptions.**

5 Conclusions and Key Takeaways

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

<u>Residential Prototype: Single-family Detached Home</u>

Home insulation primarily impacts the heating and cooling consumptions. The relative impact of insulating different envelope elements is primarily driven by their surface areas exposed to the outdoor conditions. This study showed that the wall insulation had the largest impact on the savings, followed by the attic insulation, then the basement wall insulation. This was due in part to the surface area of exterior above-grade wall is 1.5 times that of the attic exterior boundary. The basement wall insulation exhibited the smallest impact likely due to the inherent insulation characteristics of the soil surrounding the exterior surface of the basement wall.

The savings in colder climates are larger relative to temperate climates due to the dominance of space heating energy consumption. Switching to 100% heat pump systems, the amount of energy savings due to the electrification of the heating system is greatly dependant on the efficiency of the replaced system. For example, this study showed larger savings in CZ5 compared to CZ3 due to the higher penetration of heat pumps currently in CZ3 (~70% of homes) compared to CZ5 (~21% of homes).

The transition of the heating systems from fossil fuel to heat pumps is expected to reduce the total energy consumption of the home regardless of the amount of insulation provided. As such, the total energy savings from insulating the envelope would decrease, but with the benefit of allowing for a smaller sized heat pump. Thus, it is seen that both equipment efficiency and envelope efficiency have complimentary benefits on reducing energy use and carbon emissions.

The carbon payback period was found to be under a year for all simulated cases. Shorter payback periods were observed in CZ5, despite the higher embodied carbon, due to the much larger first year GHG savings relative to CZ3. This highlights the critical role of insulation in heating dominant regions. The GHG emission savings over the lifetime of the investigated plastic insulation were found to be one to two orders of magnitude higher than the embodied carbon for the respective scenarios.

Commercial Prototype: Medium Office Building

This study demonstrated that the roof insulation has the largest impact on the savings, followed by the exterior wall insulation, then the slab perimeter insulation. This was due in part to the surface area of roof is 1.25 times that of the exterior above-grade wall. The impact of the slab perimeter insulation was shown to be much lower likely due to the dominant effect of the exterior walls on the ground floor in addition to the inherent insulation characteristics of the soil surrounding the slab perimeter. Besides, the application of the insulation only to the slab perimeter and the inherent limitations in the F-factor method used to simulate the heat losses through the slab may contribute to the underestimation of the slab insulation impact.

One interesting observation on cooling electricity consumption and savings in CZ5 was that the scenarios with partial insulation showed lower consumption and larger savings than the scenario of full building insulation. Also, the scenario with no roof insulation exhibited larger cooling consumption than the scenario with no insulation, indicating negative savings in cooling electricity use. Such behaviors are likely attributed to the effect of insulation on reducing the free cooling imparted by the cooler outdoor temperatures during summer in CZ5. Scenario 2 showed that the average office generally exhibits lower electricity consumption due to the transition to 100% heat pump systems.

Similar to the residential prototype, the maximum carbon payback period among all simulated scenarios of the commercial prototype was found to be 13 months for CZ3, and 7.7 months for CZ5. The only exception to this is the scenario with slab perimeter insulation which displayed negative savings due primarily to modeling limitations. The carbon avoidance ratio for the case with whole office insulation ranged between 18-208 for CZ3 and 29-305 for CZ5, depending on the heating system scenario and the future predictions of emission rates from electricity generation.

Appendix A

Figure A. 1 to Figure A. 12 show the lifetime carbon savings from the different insulation scenarios applied to the residential prototype in climate zones 3 and 5 under Scenario 1: Current Heating Systems Mix. Figure A. 13 to Figure A. 24 show the lifetime carbon savings from the different insulation scenarios applied to the residential prototype in climate zones 3 and 5 under Scenario 2: 100% Heat Pump System. The cumulative GHG savings are displayed over 75 years (2024-2098) using high, medium and low RE cost scenarios, respectively, for electricity emission rates. Note that the embodied carbon is shown as a horizontal line at the base of the charts and represents the total life-cycle embodied carbon emissions associated with the insulation materials, irrespective of when those emissions occur in the life-cycle. It is clear that with the increased penetration of RE technologies in the electricity generation sector the GHG savings potential of energy conservation measures such as insulation will decrease, resulting in longer carbon payback periods. But, for the foreseeable future significant net carbon savings will continue to occur under all the future scenarios considered.

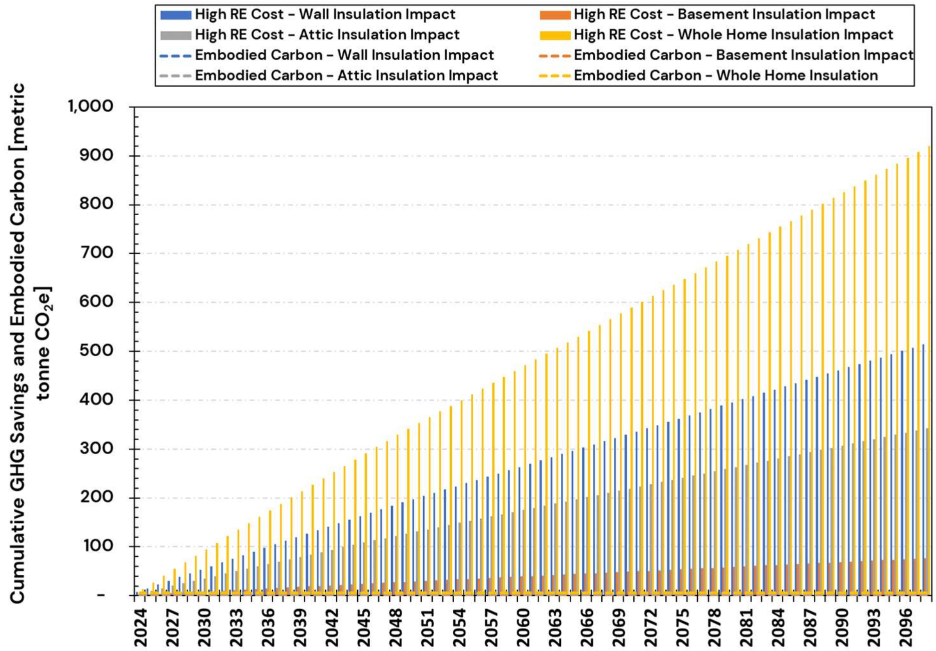

Figure A. 1: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using High RE Cost Electricity Emission Rates for CZ3 – Scenario 1: Current Heating Systems Mix

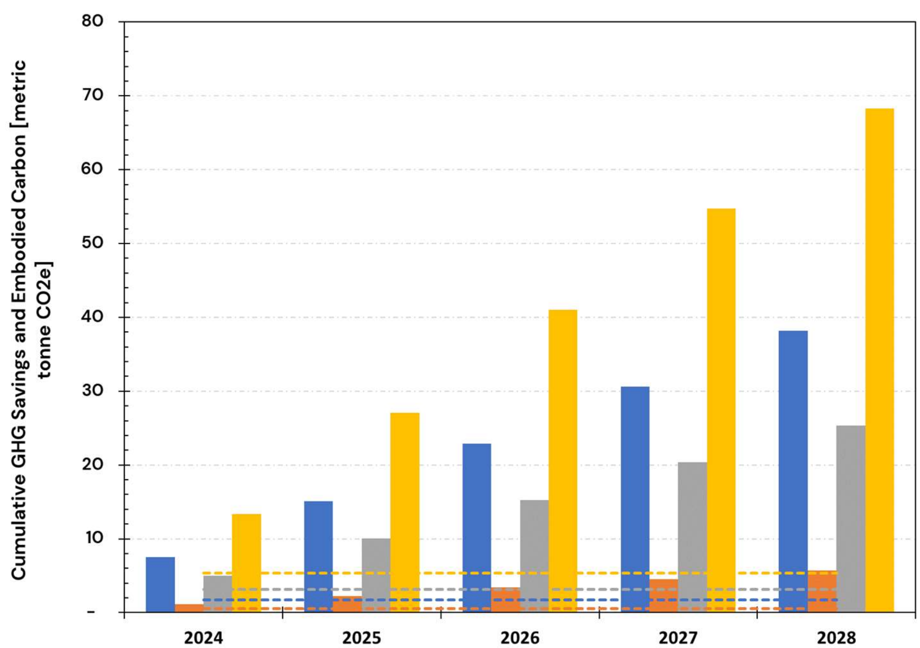

Figure A. 2: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using High RE Cost Electricity Emission Rates for CZ3 – Scenario 1: Current Heating Systems Mix

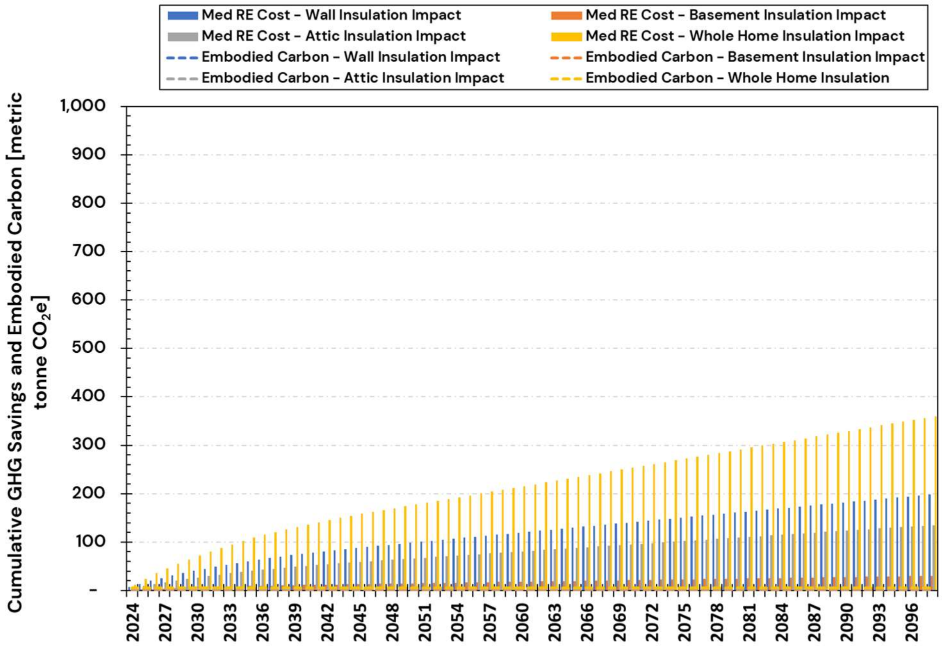

Figure A. 3: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using Medium RE Cost Electricity Emission Rates for CZ3 – Scenario 1: Current Heating Systems Mix

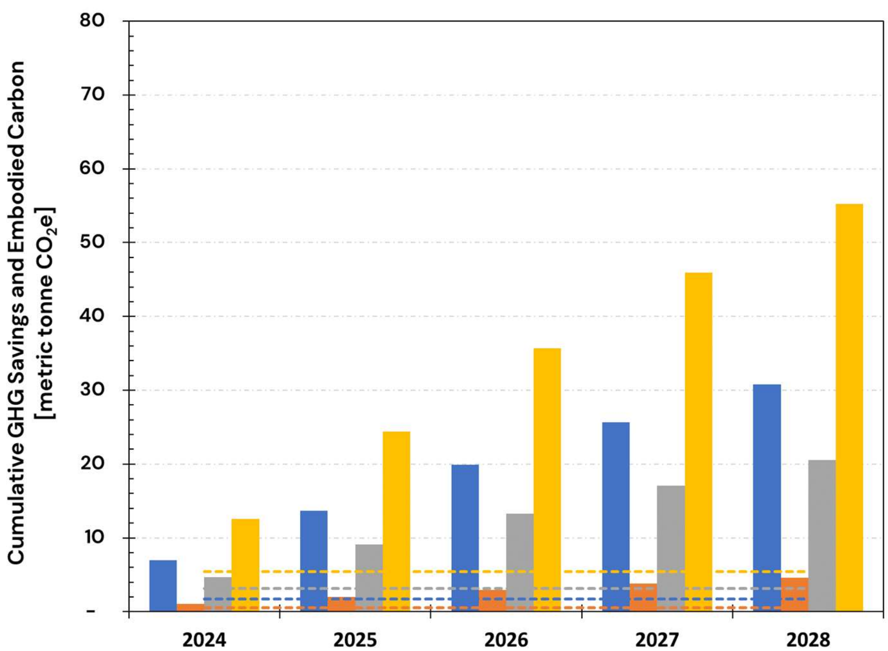

Figure A. 4: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using Medium RE Cost Electricity Emission Rates for CZ3 – Scenario 1: Current Heating Systems Mix

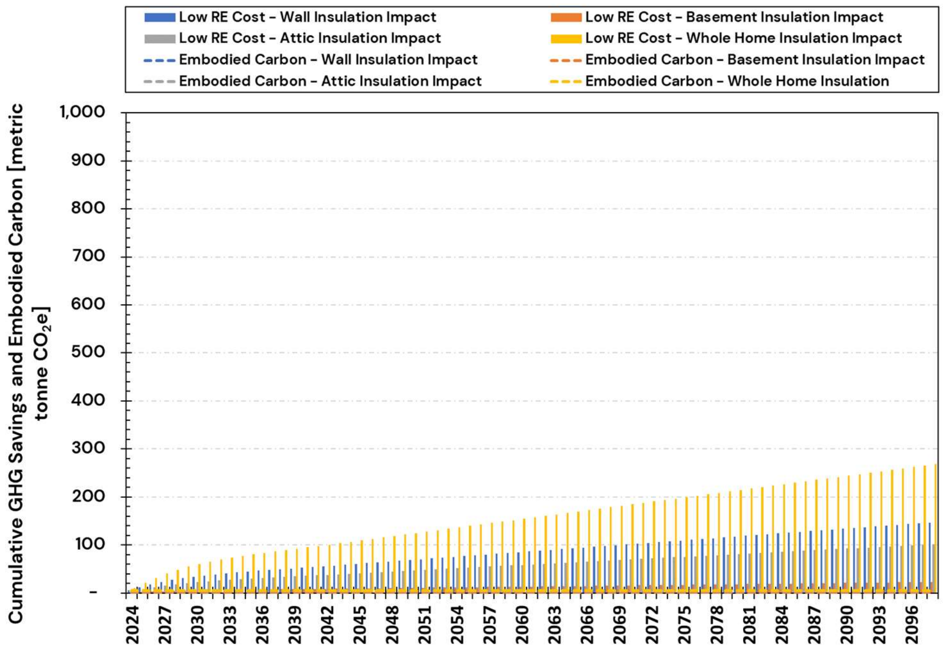

Figure A. 5: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using Low RE Cost Electricity Emission Rates for CZ3 – Scenario 1: Current Heating Systems Mix

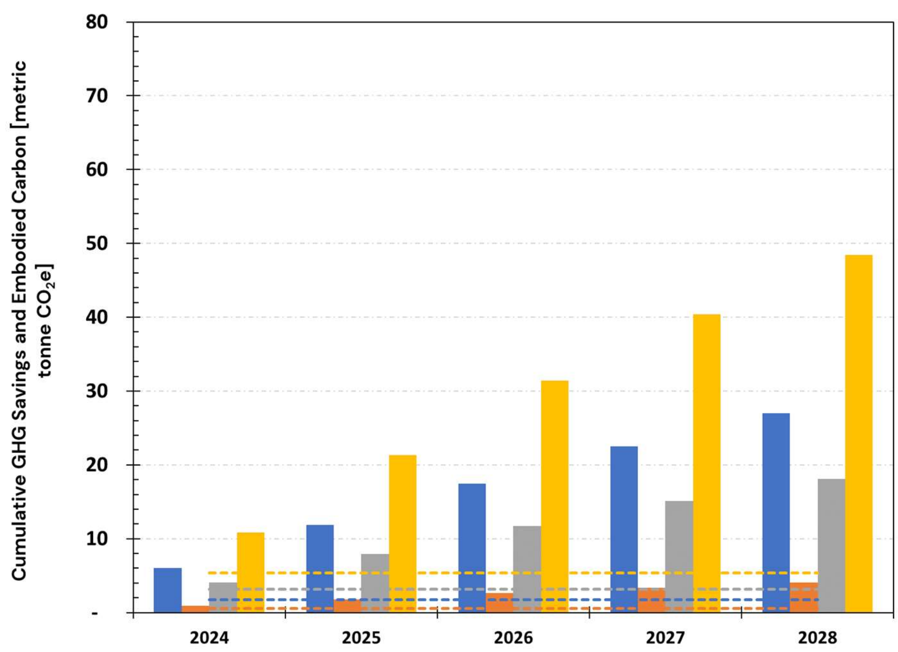

Figure A. 6: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using Low RE Cost Electricity Emission Rates for CZ3 – Scenario 1: Current Heating Systems Mix

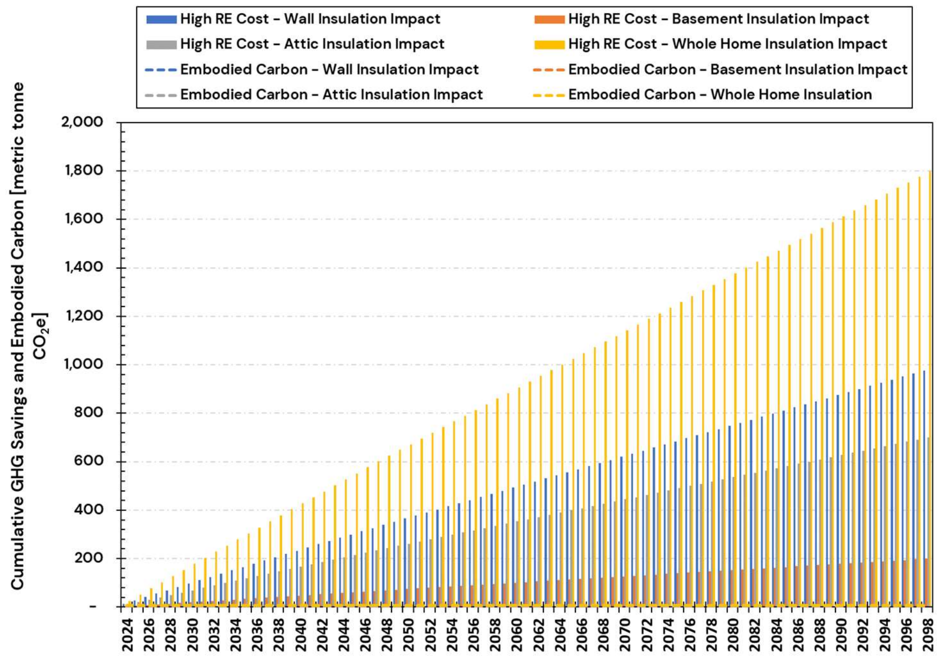

Figure A. 7: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using High RE Cost Electricity Emission Rates for CZ5 – Scenario 1: Current Heating Systems Mix

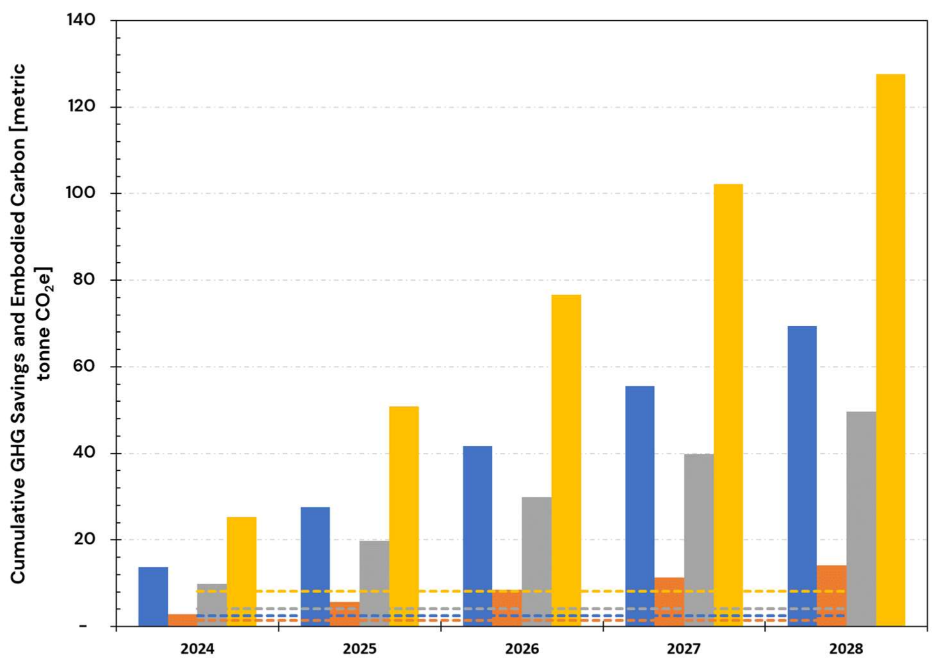

Figure A. 8: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using High RE Cost Electricity Emission Rates for CZ5 – Scenario 1: Current Heating Systems Mix

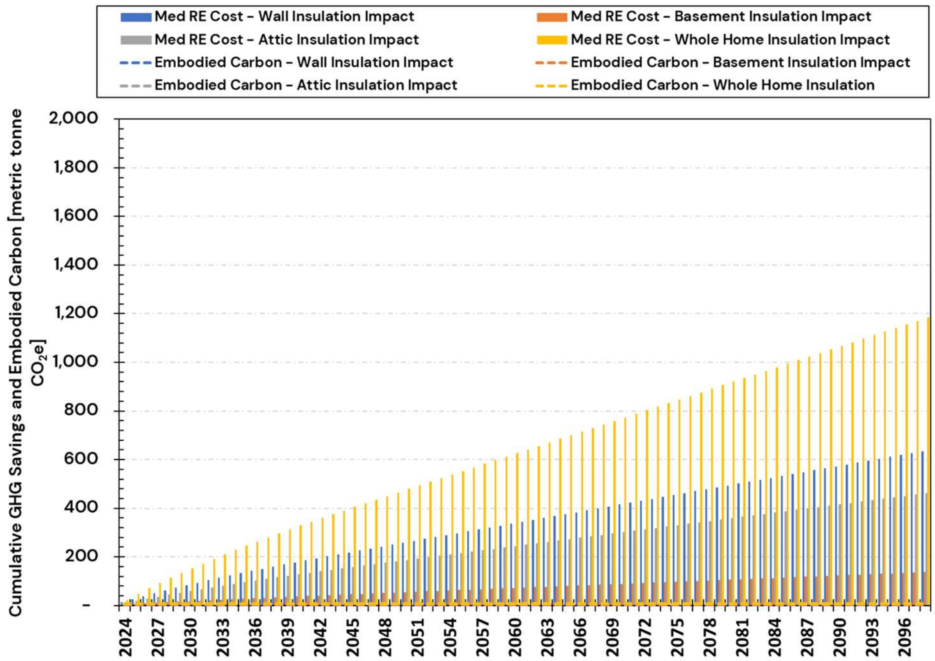

Figure A. 9: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using Medium RE Cost Electricity Emission Rates for CZ5 – Scenario 1: Current Heating Systems Mix

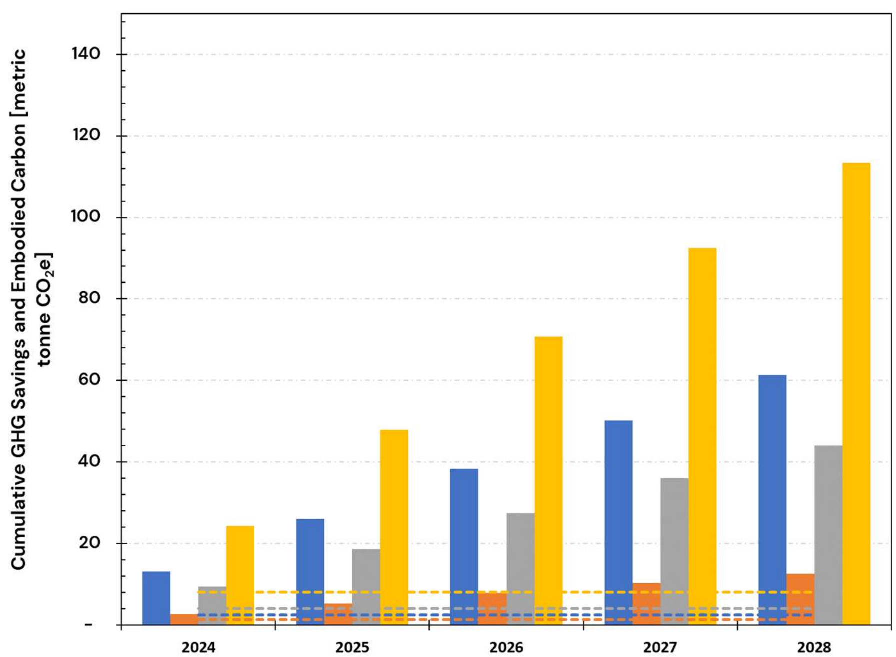

Figure A. 10: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using Medium RE Cost Electricity Emission Rates for CZ5 – Scenario 1: Current Heating Systems Mix

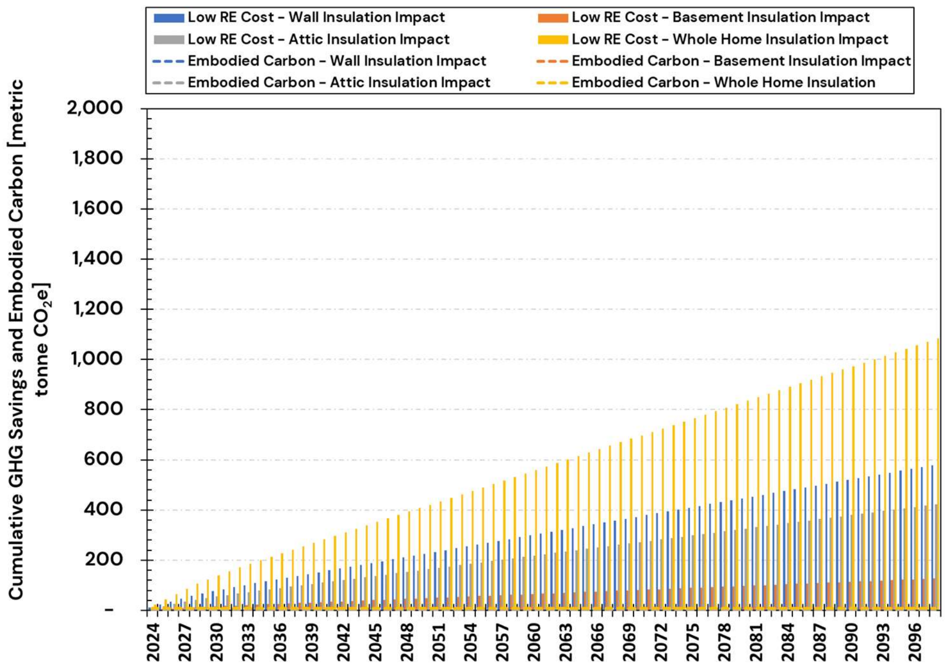

Figure A. 11: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using Low RE Cost Electricity Emission Rates for CZ5 – Scenario 1: Current Heating Systems Mix

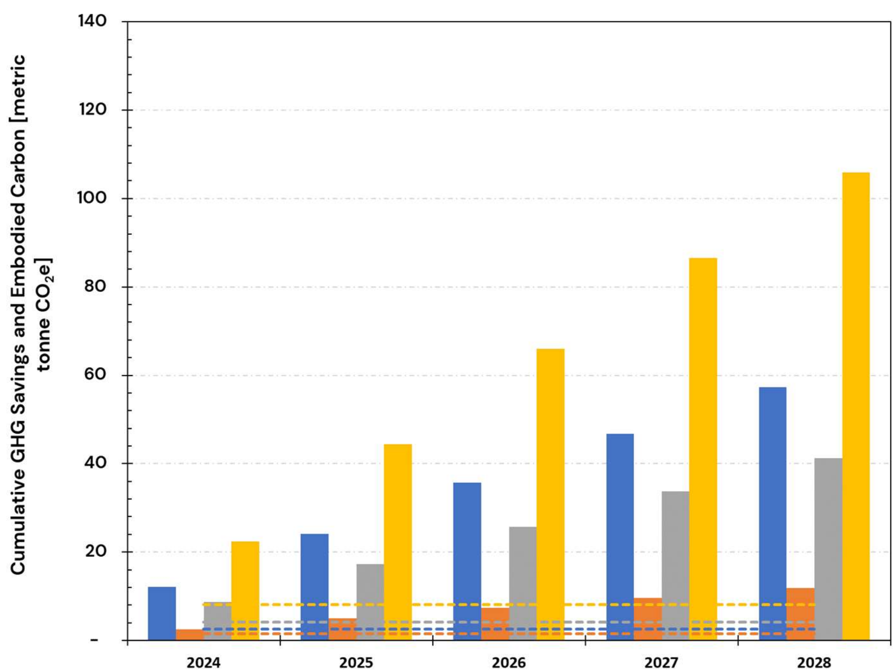

Figure A. 12: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using Low RE Cost Electricity Emission Rates for CZ5 – Scenario 1: Current Heating Systems Mix

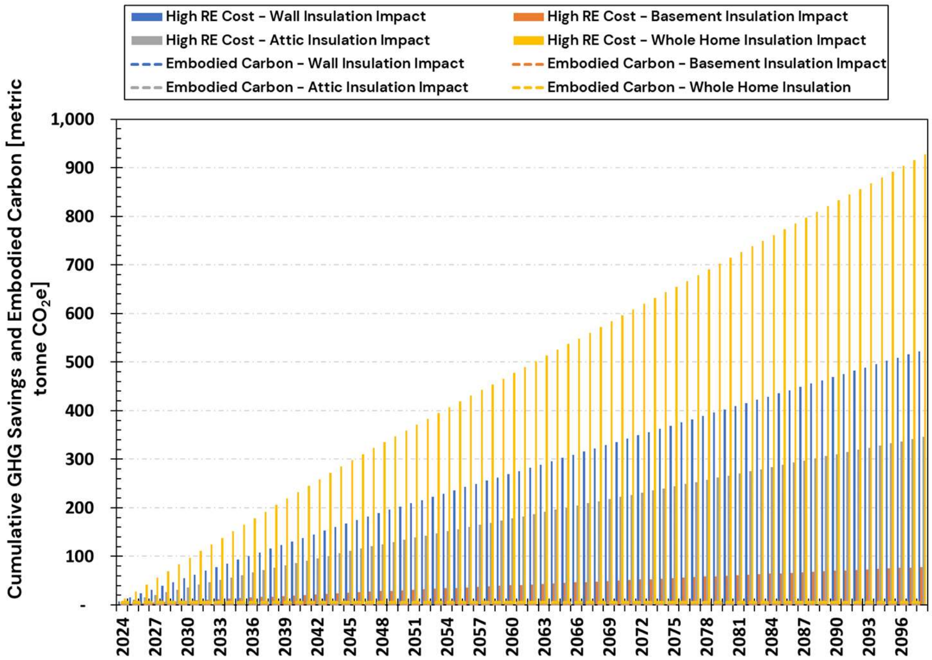

Figure A. 13: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using High RE Cost Electricity Emission Rates for CZ3 – Scenario 2: 100% Heat Pump Systems

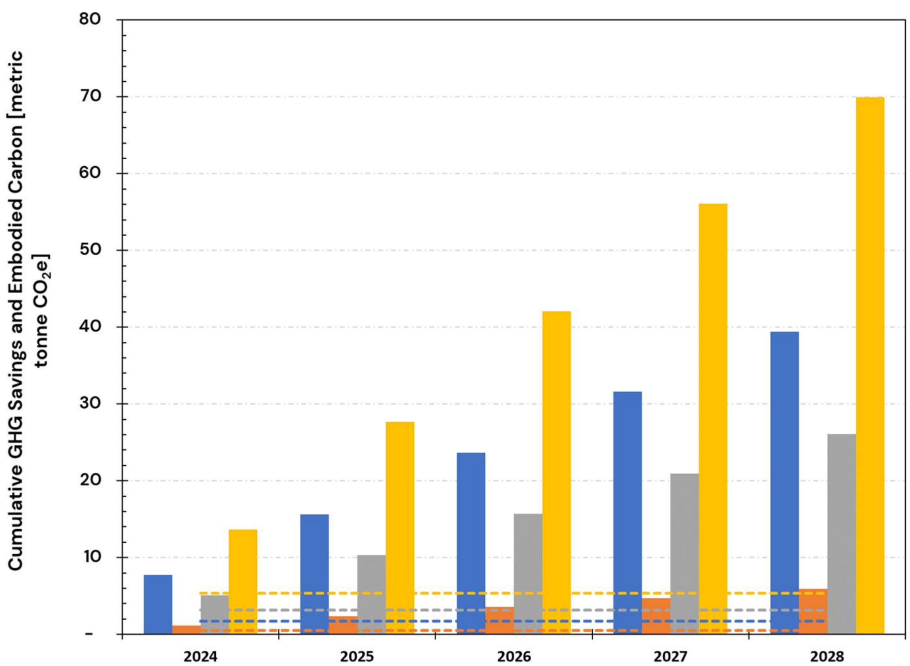

Figure A. 14: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using High RE Cost Electricity Emission Rates for CZ3 – Scenario 2: 100% Heat Pump Systems

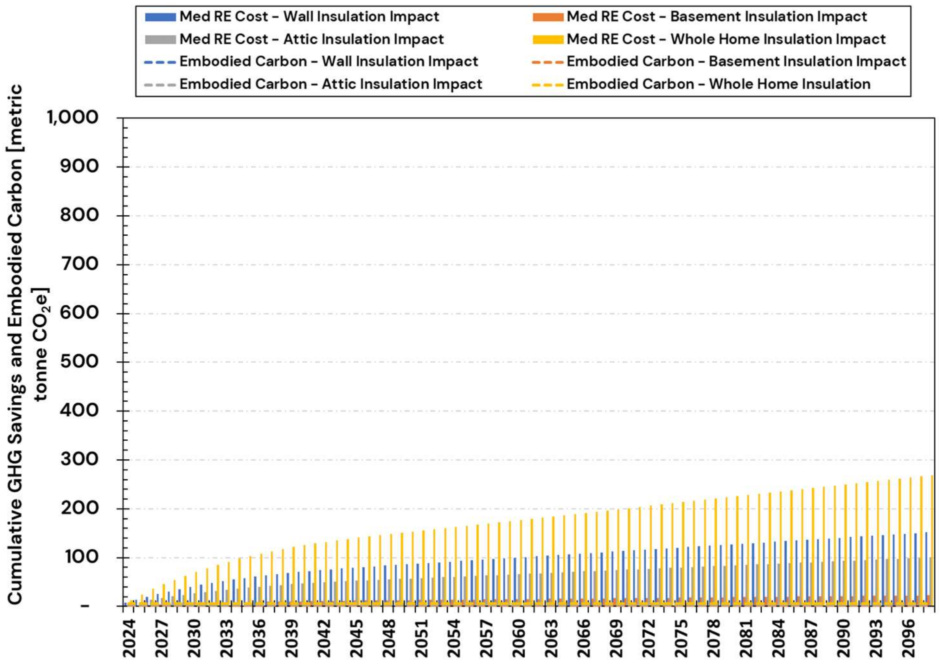

Figure A. 15: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using Medium RE Cost Electricity Emission Rates for CZ3 – Scenario 2: 100% Heat Pump Systems

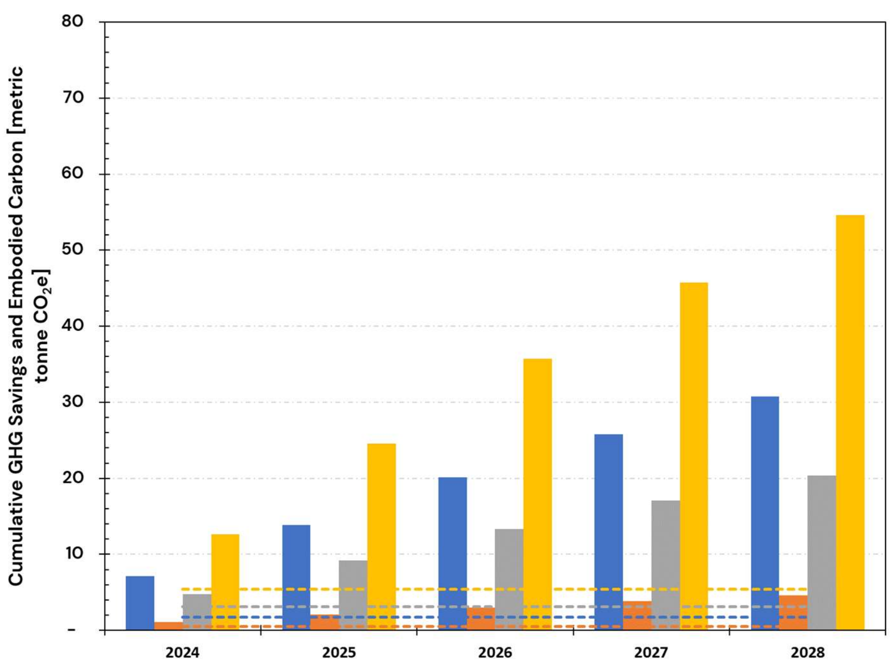

Figure A. 16: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using Medium RE Cost Electricity Emission Rates for CZ3 – Scenario 2: 100% Heat Pump Systems

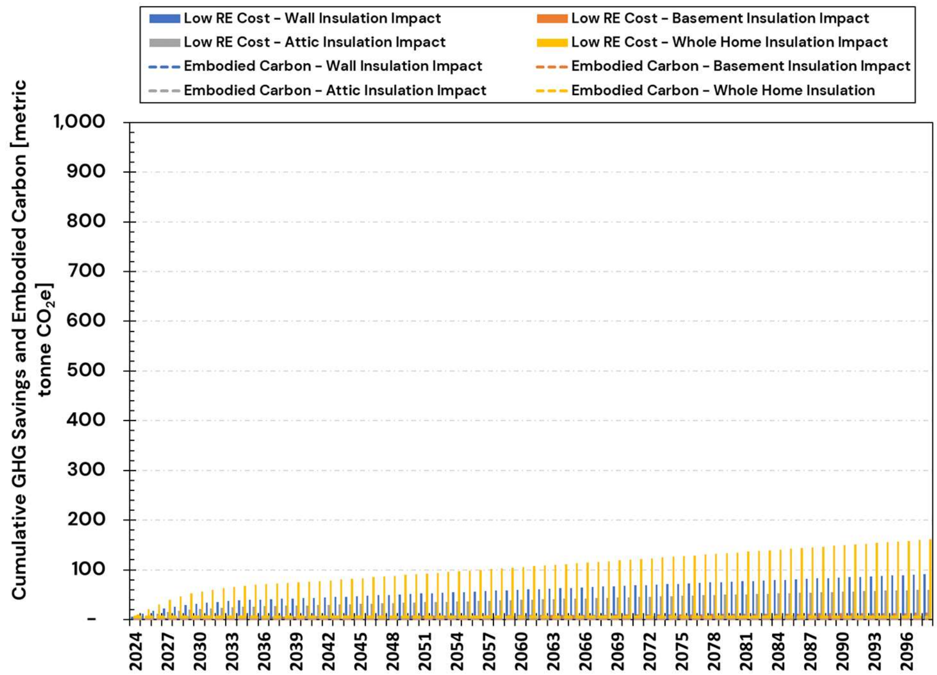

Figure A. 17: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using Low RE Cost Electricity Emission Rates for CZ3 – Scenario 2: 100% Heat Pump Systems

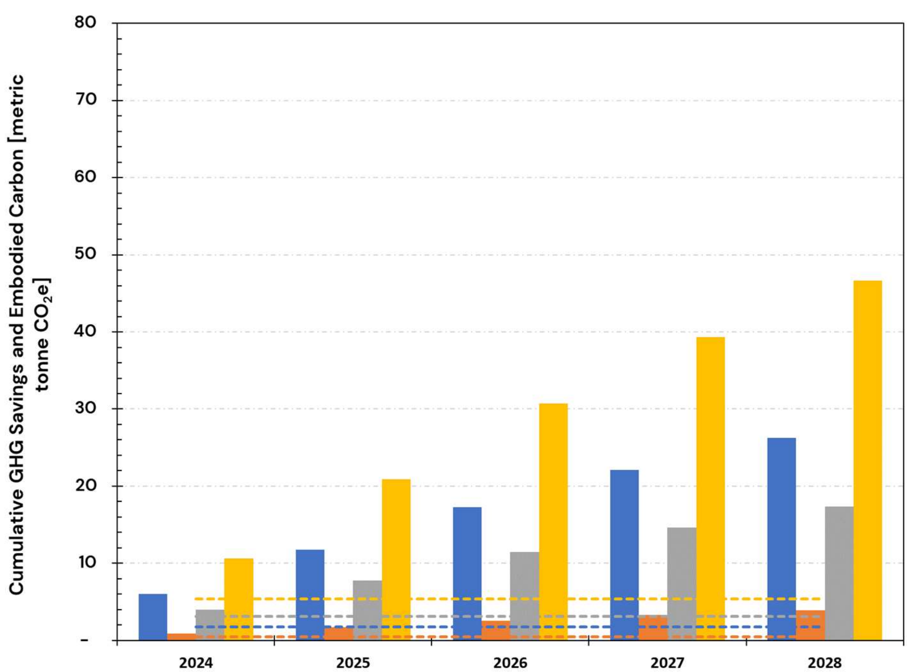

Figure A. 18: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using Low RE Cost Electricity Emission Rates for CZ3 – Scenario 2: 100% Heat Pump Systems

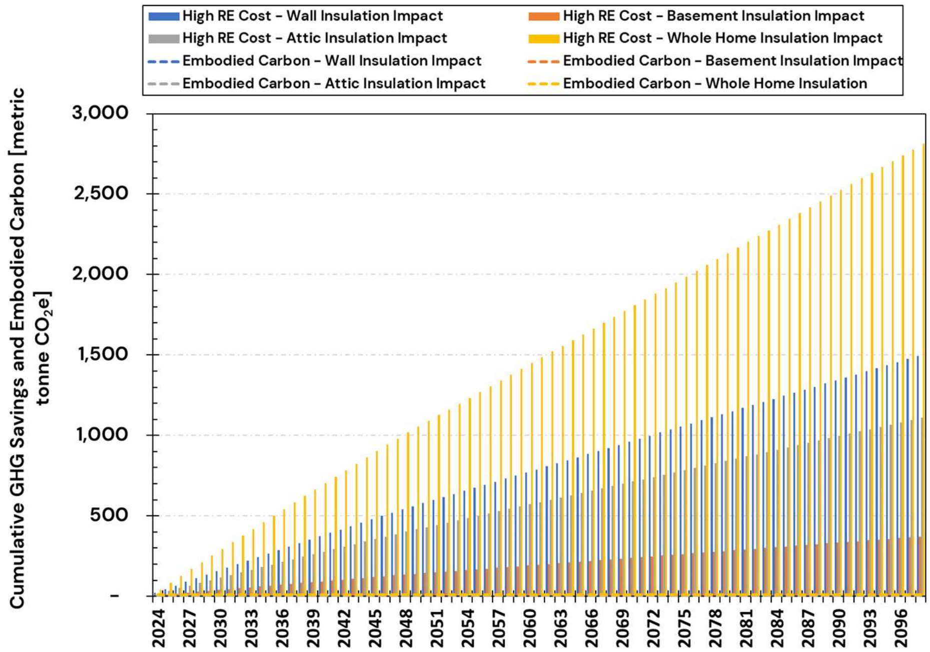

Figure A. 19: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using High RE Cost Electricity Emission Rates for CZ5 – Scenario 2: 100% Heat Pump Systems

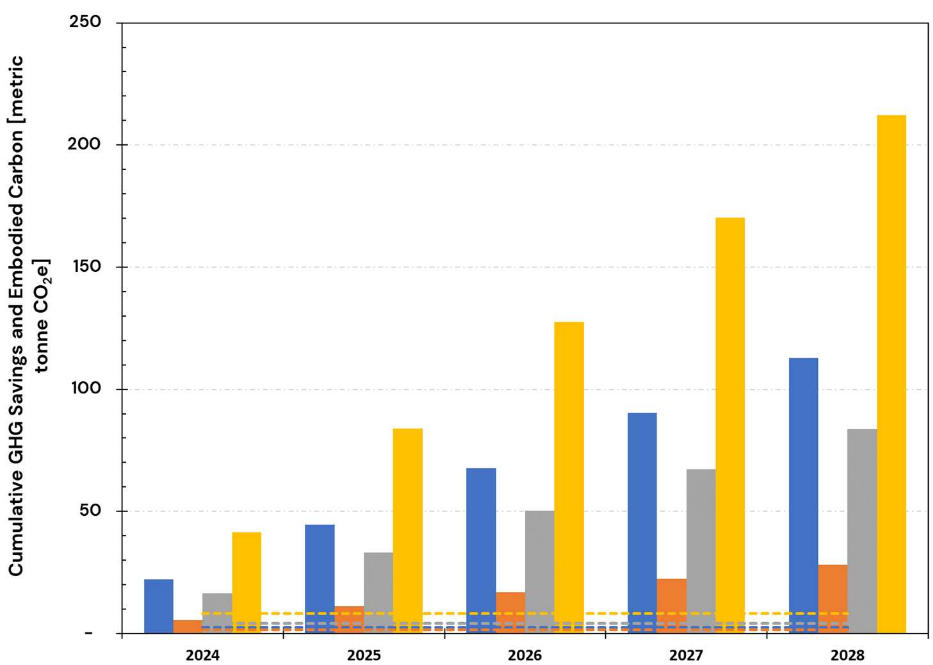

Figure A. 20: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using High RE Cost Electricity Emission Rates for CZ5 – Scenario 2: 100% Heat Pump Systems

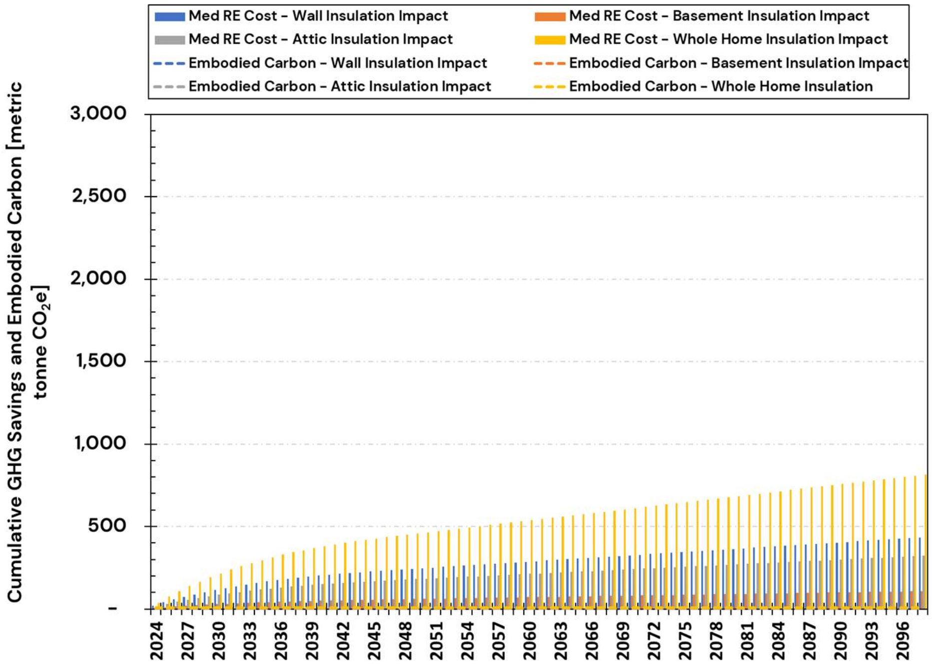

Figure A. 21: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using Medium RE Cost Electricity Emission Rates for CZ5 – Scenario 2: 100% Heat Pump Systems

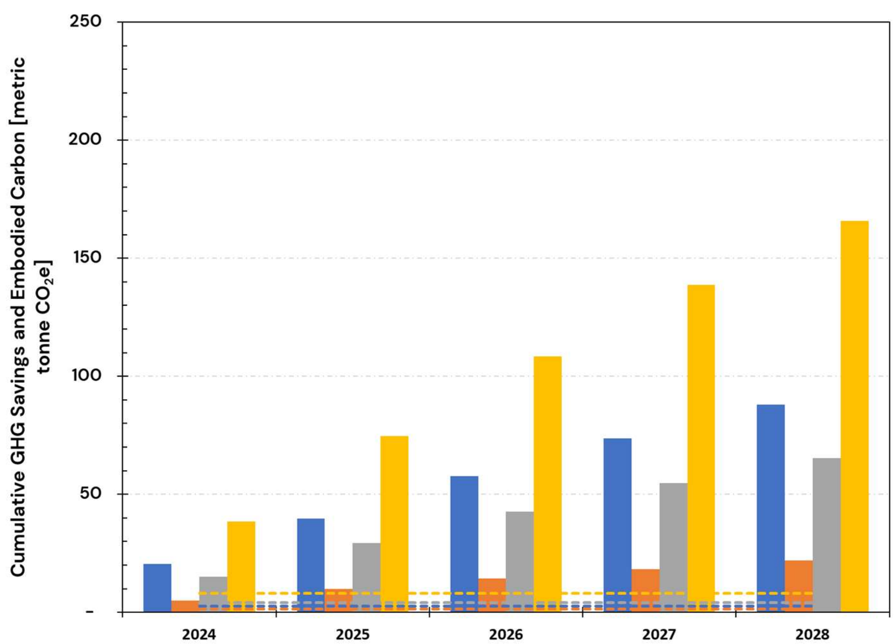

Figure A. 22: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using Medium RE Cost Electricity Emission Rates for CZ5 – Scenario 2: 100% Heat Pump Systems

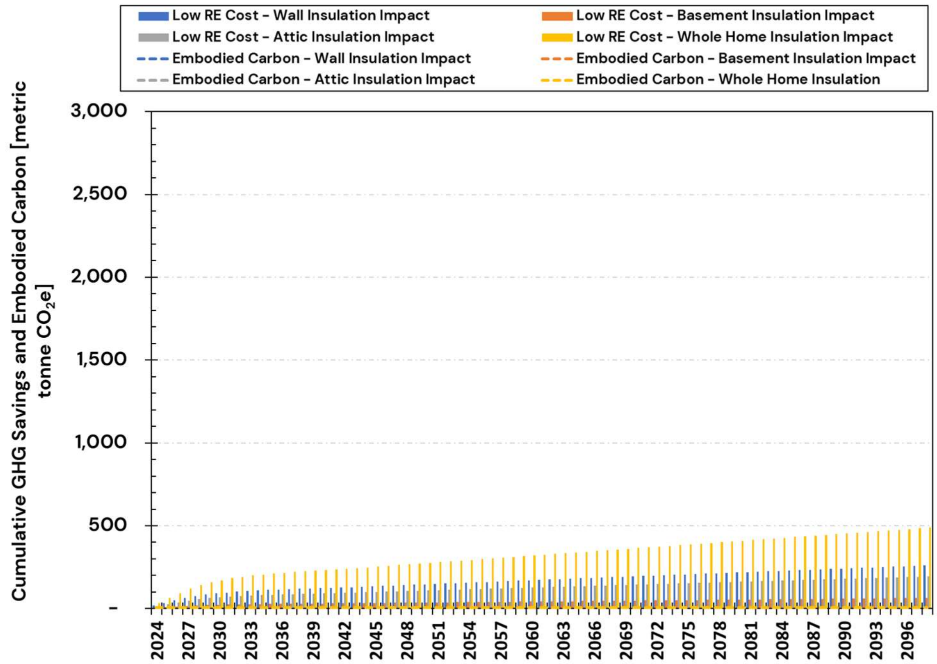

Figure A. 23: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using Low RE Cost Electricity Emission Rates for CZ5 – Scenario 2: 100% Heat Pump Systems

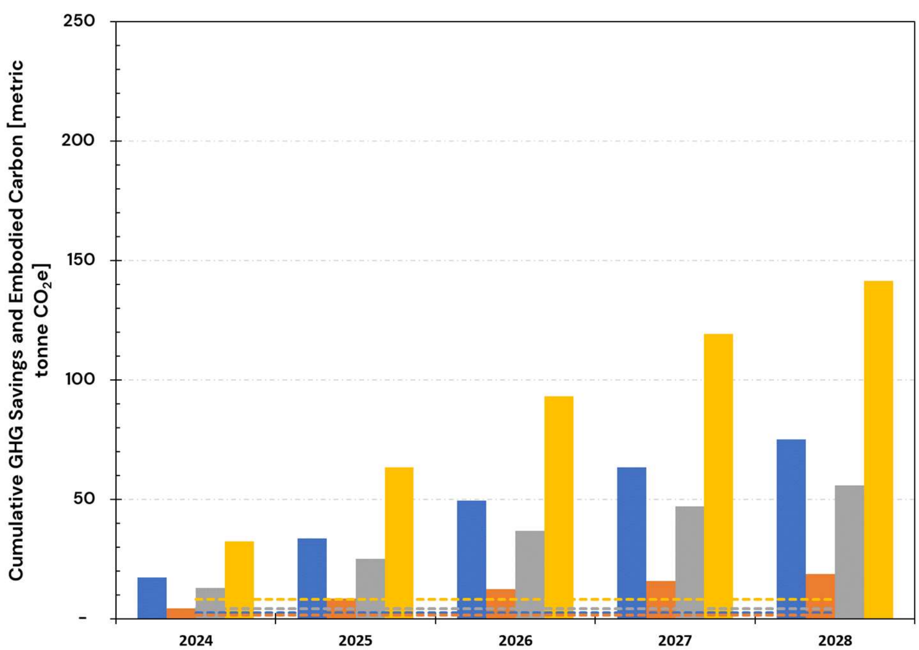

Figure A. 24: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using Low RE Cost Electricity Emission Rates for CZ5 – Scenario 2: 100% Heat Pump Systems

Figure A. 25 to Figure A. 36 show the lifetime carbon savings from the different insulation scenarios applied to the commercial prototype in climate zones 3 and 5 under Scenario 1: Natural Gas Heating. Figure A. 37 to Figure A. 48 show the lifetime carbon savings from the different insulation scenarios applied to the residential prototype in climate zones 3 and 5 under Scenario 2: 100% Heat Pump System. The cumulative GHG savings are displayed over 75 years (2024-2098) using high, medium and low RE cost scenarios, respectively, for electricity emission rates. Note that the embodied carbon is shown as a horizontal line at the base of the charts and represents the total life-cycle embodied carbon emissions associated with the insulation materials, irrespective of when those emissions occur in the life-cycle. It is clear that with the increased penetration of RE technologies in the electricity generation sector the GHG savings potential of energy conservation measures such as insulation will decrease, resulting in longer carbon payback periods. But, for the foreseeable future significant net carbon savings will continue to occur under all the future scenarios considered.

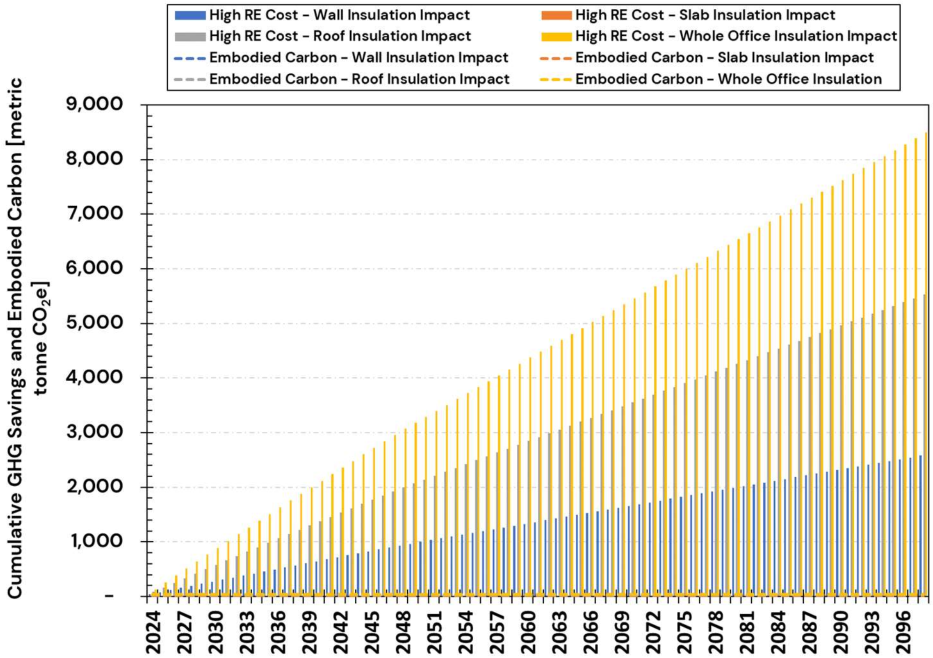

Figure A. 25: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using High RE Cost Electricity Emission Rates for CZ3 – Scenario 1: Natural Gas Heating

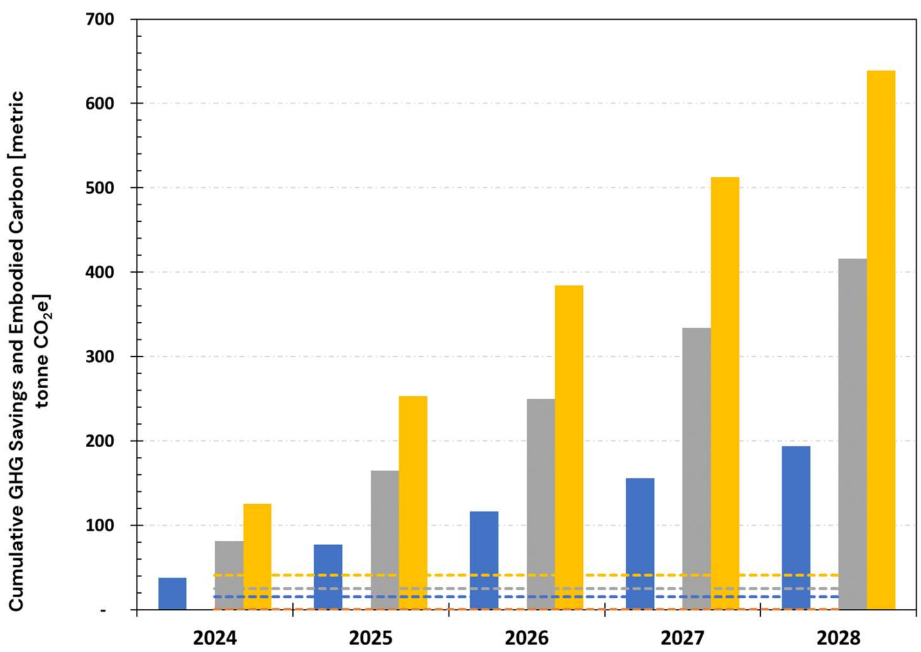

Figure A. 26: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using High RE Cost Electricity Emission Rates for CZ3 – Scenario 1: Natural Gas Heating

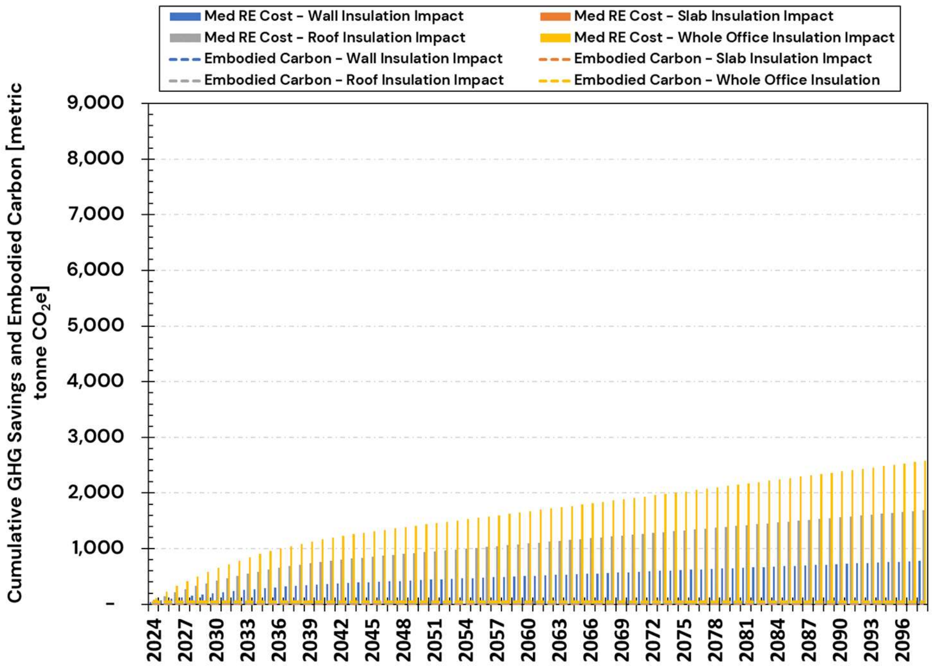

Figure A. 27: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using Medium RE Cost Electricity Emission Rates for CZ3 – Scenario 1: Natural Gas Heating

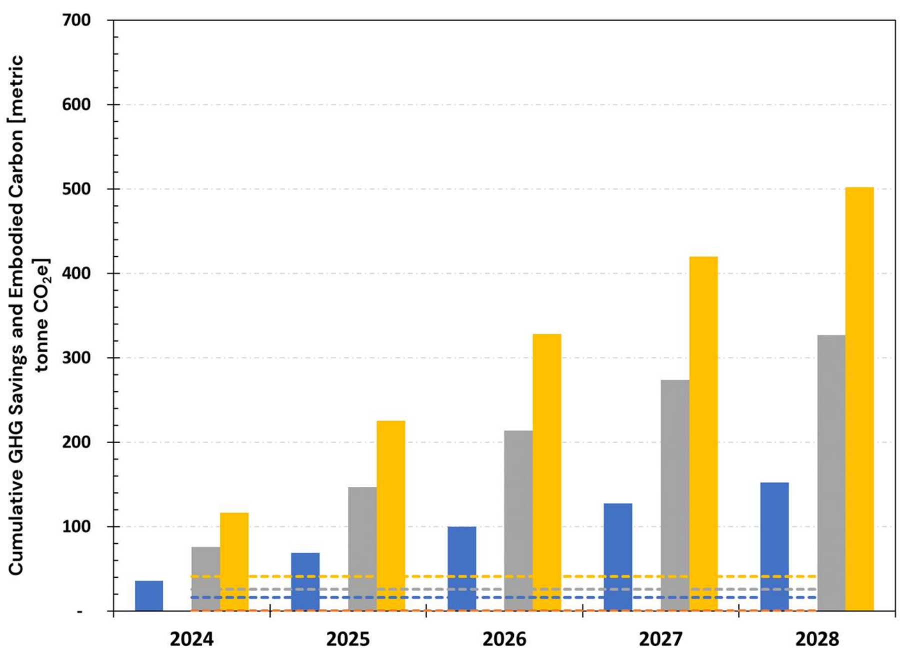

Figure A. 28: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using Medium RE Cost Electricity Emission Rates for CZ3 – Scenario 1: Natural Gas Heating

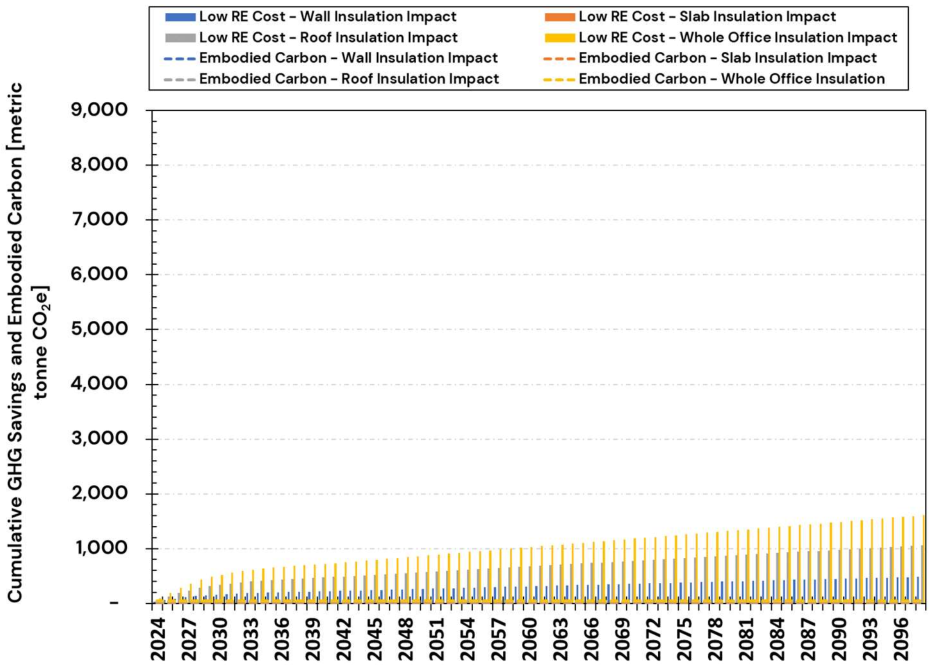

Figure A. 29: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using Low RE Cost Electricity Emission Rates for CZ3 – Scenario 1: Natural Gas Heating

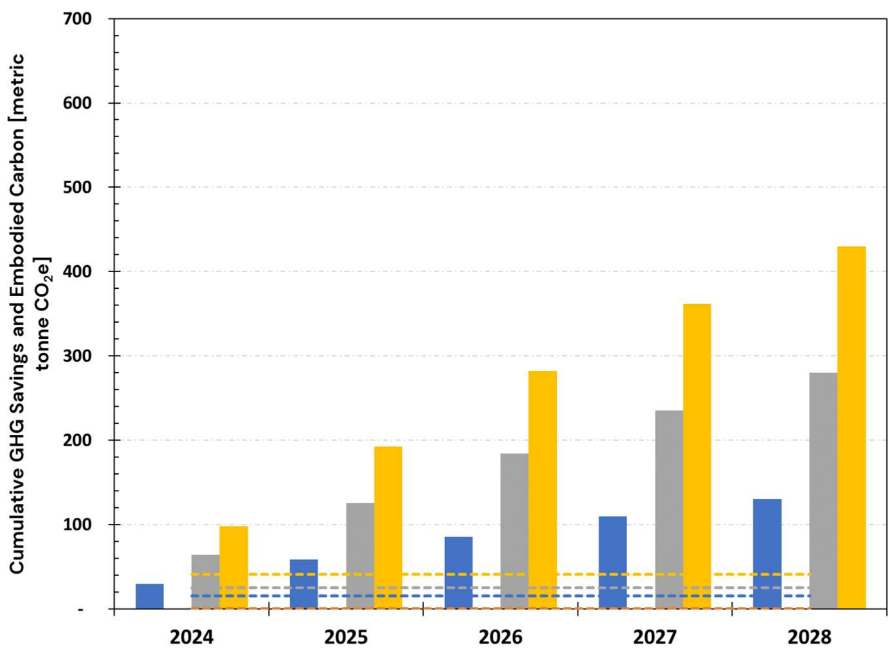

Figure A. 30: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using Low RE Cost Electricity Emission Rates for CZ3 – Scenario 1: Natural Gas Heating

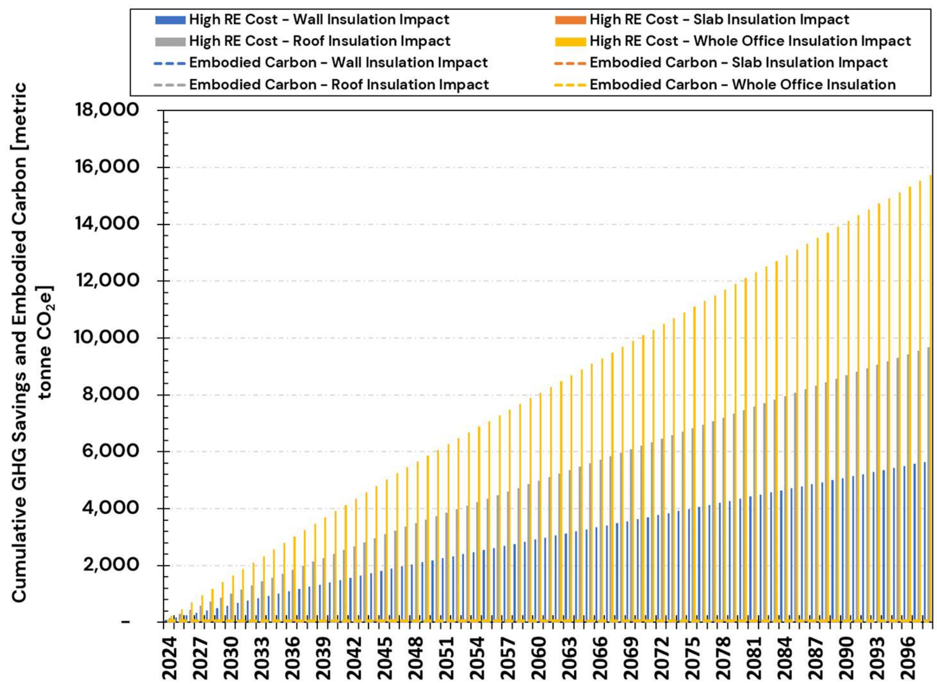

Figure A. 31: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using High RE Cost Electricity Emission Rates for CZ5 – Scenario 1: Natural Gas Heating

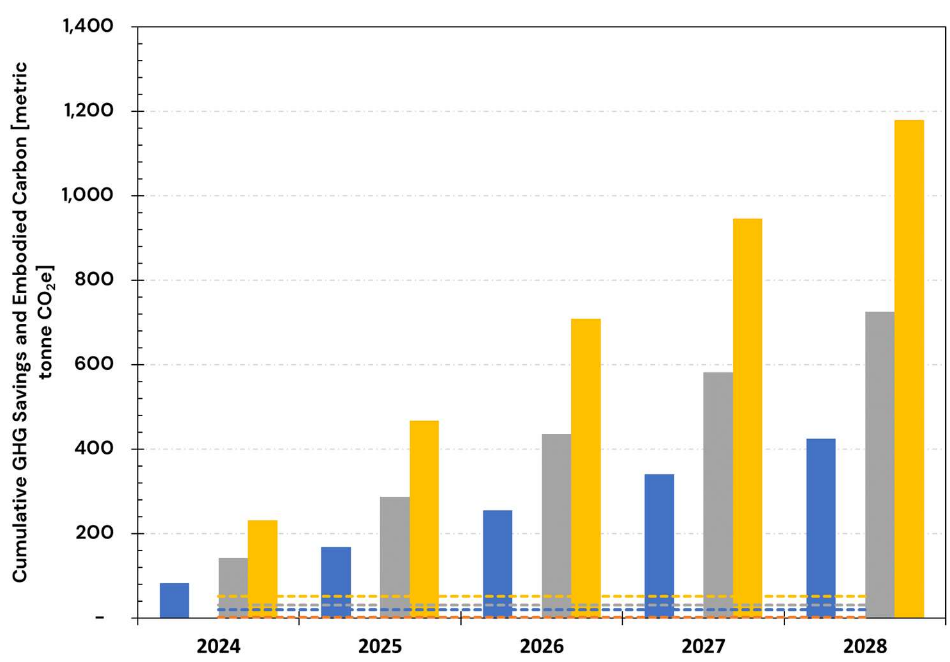

Figure A. 32: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using High RE Cost Electricity Emission Rates for CZ5 – Scenario 1: Natural Gas Heating

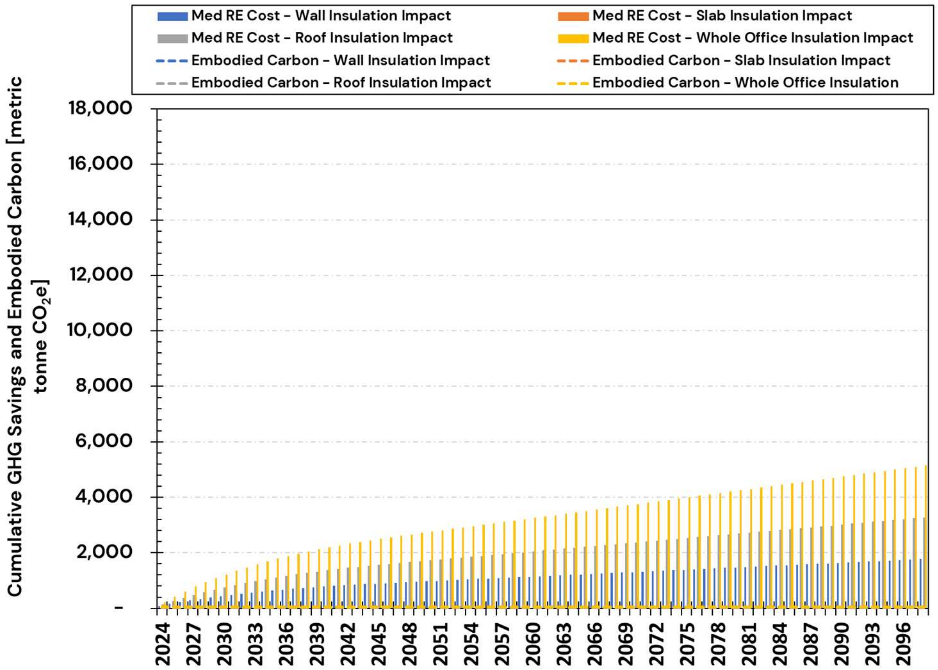

Figure A. 33: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using Medium RE Cost Electricity Emission Rates for CZ5 – Scenario 1: Natural Gas Heating

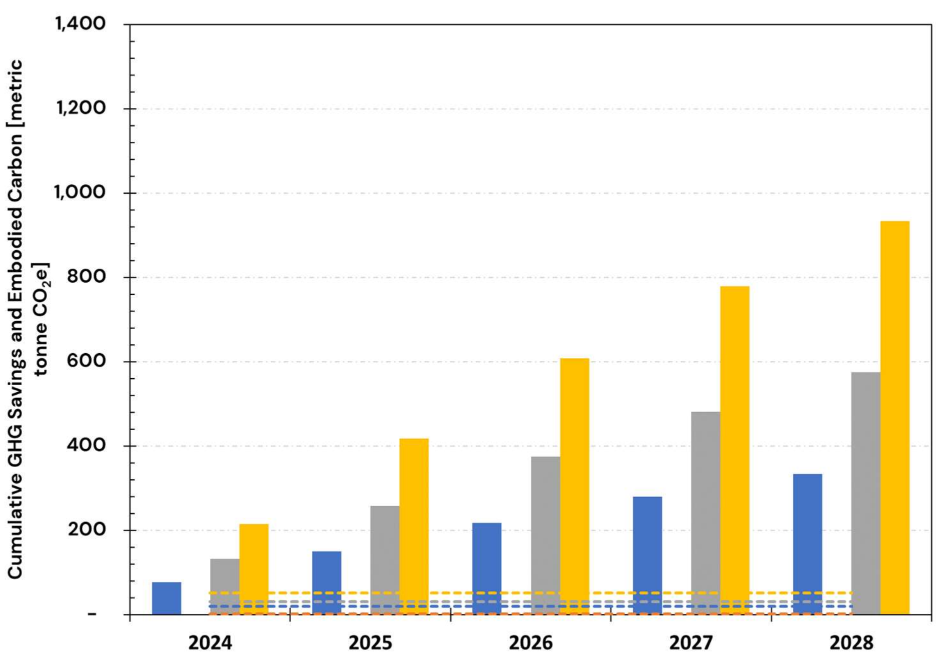

Figure A. 34: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using Medium RE Cost Electricity Emission Rates for CZ5 – Scenario 1: Natural Gas Heating

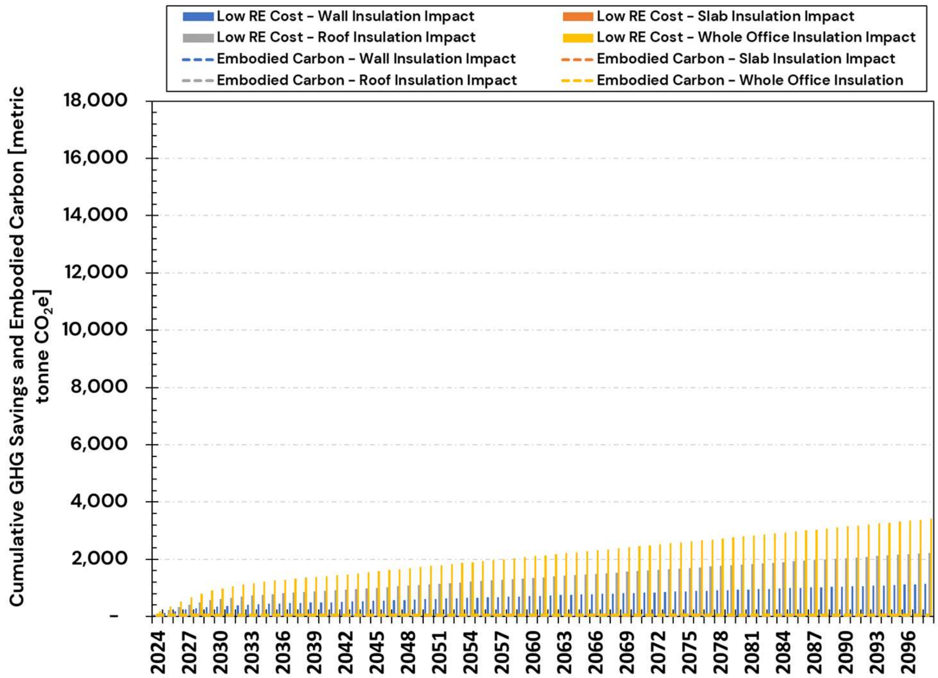

Figure A. 35: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using Low RE Cost Electricity Emission Rates for CZ5 – Scenario 1: Natural Gas Heating

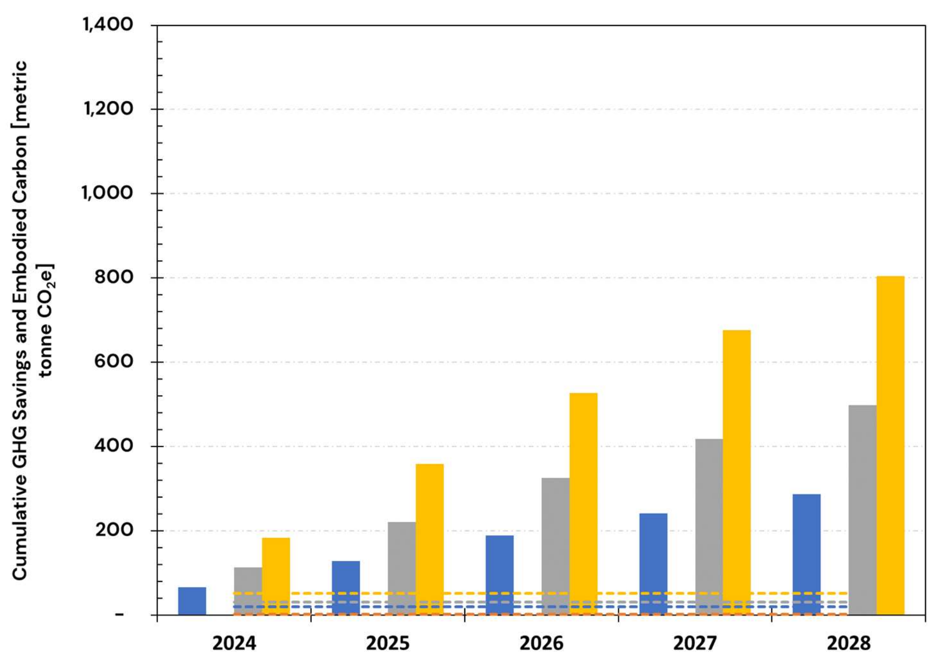

Figure A. 36: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using Low RE Cost Electricity Emission Rates for CZ5 – Scenario 1: Natural Gas Heating

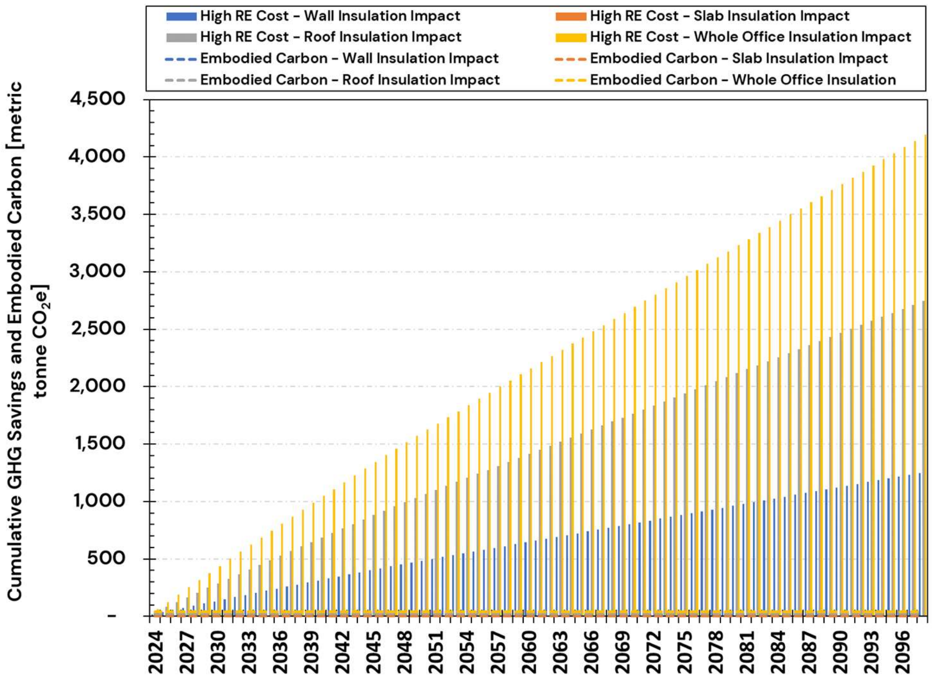

Figure A. 37: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using High RE Cost Electricity Emission Rates for CZ3 – Scenario 2: 100% Heat Pump Systems

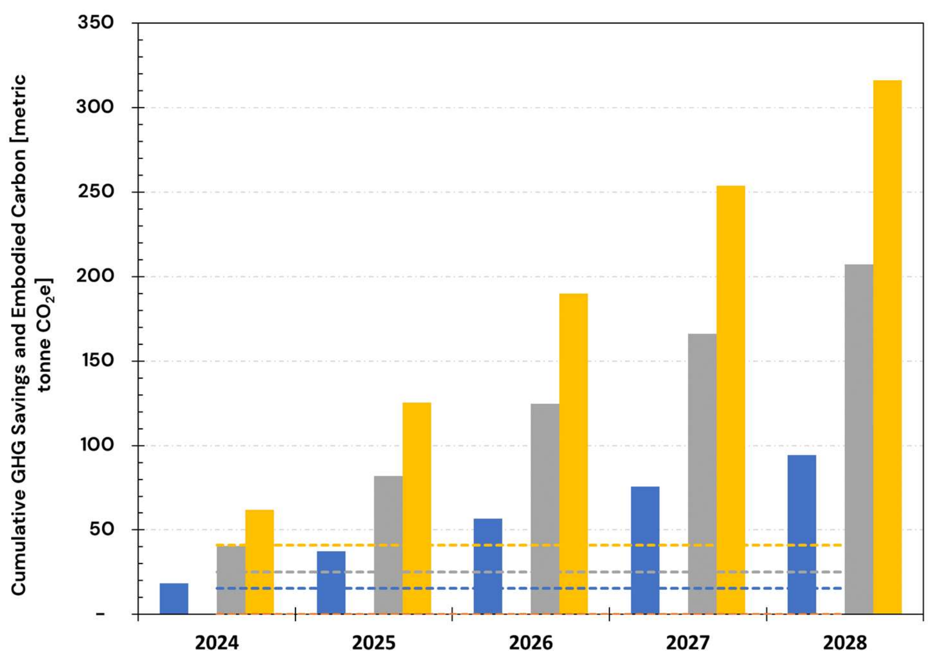

Figure A. 38: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using High RE Cost Electricity Emission Rates for CZ3 – Scenario 2: 100% Heat Pump Systems

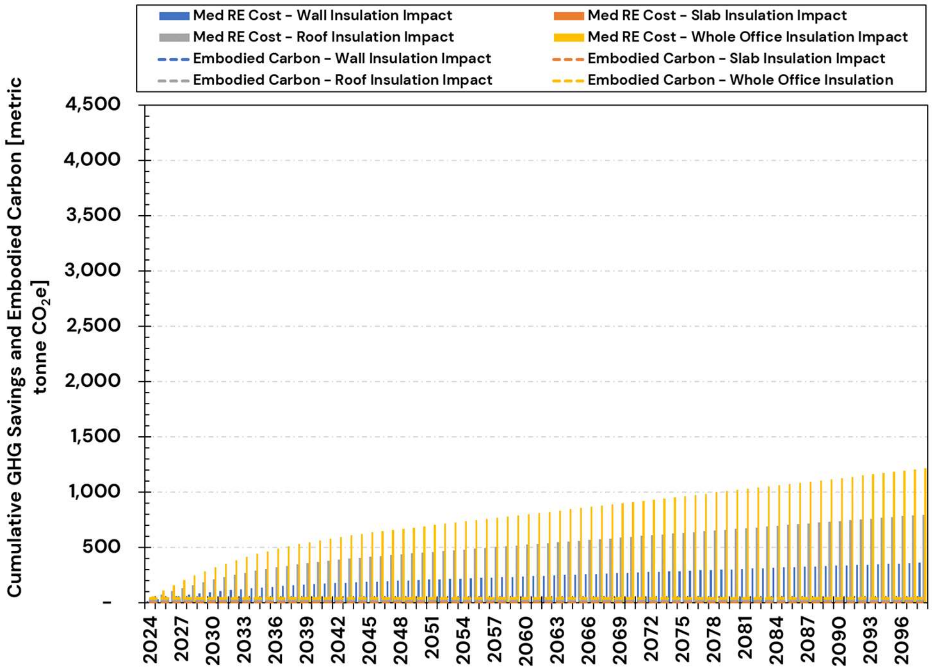

Figure A. 39: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using Medium RE Cost Electricity Emission Rates for CZ3 – Scenario 2: 100% Heat Pump Systems

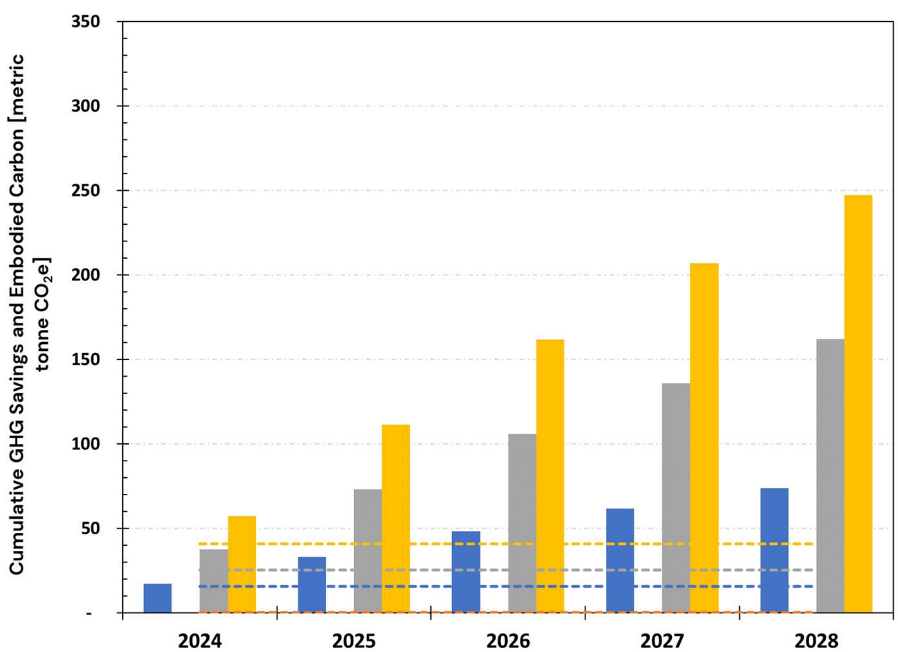

Figure A. 40: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using Medium RE Cost Electricity Emission Rates for CZ3 – Scenario 2: 100% Heat Pump Systems

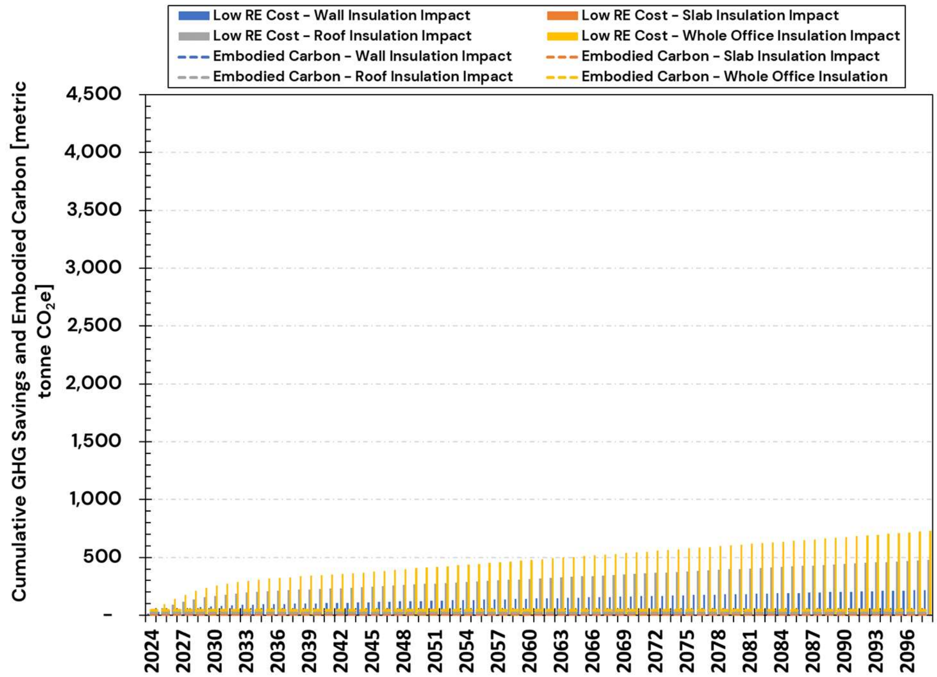

Figure A. 41: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using Low RE Cost Electricity Emission Rates for CZ3 – Scenario 2: 100% Heat Pump Systems

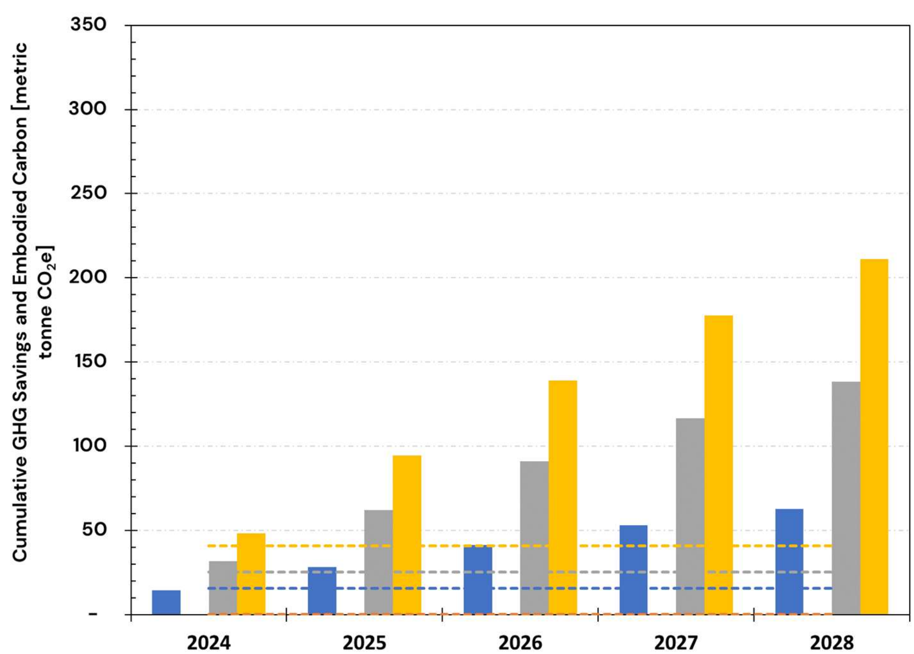

Figure A. 42: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using Low RE Cost Electricity Emission Rates for CZ3 – Scenario 2: 100% Heat Pump Systems

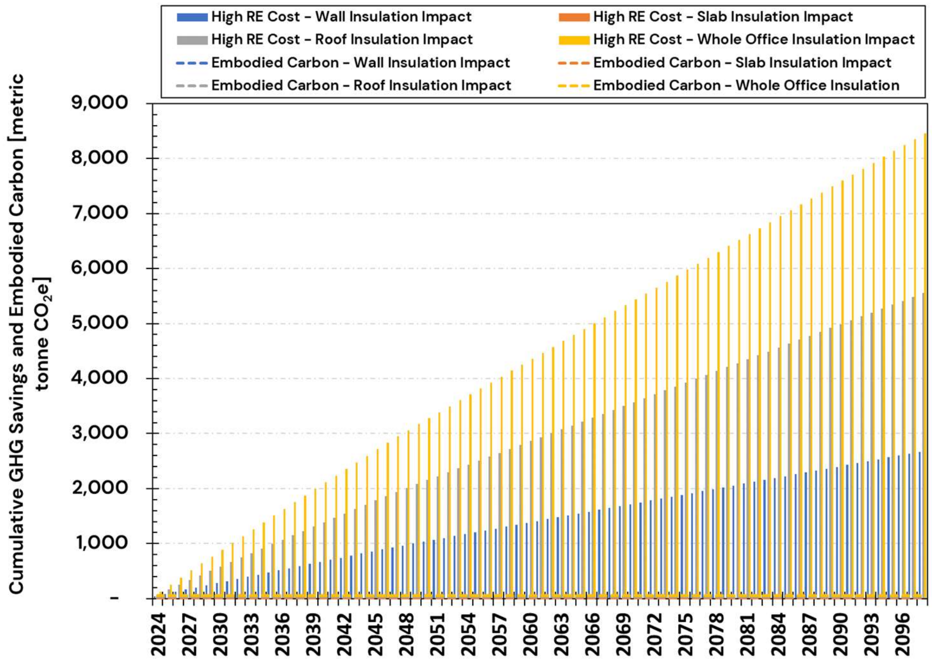

Figure A. 43: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using High RE Cost Electricity Emission Rates for CZ5 – Scenario 2: 100% Heat Pump Systems

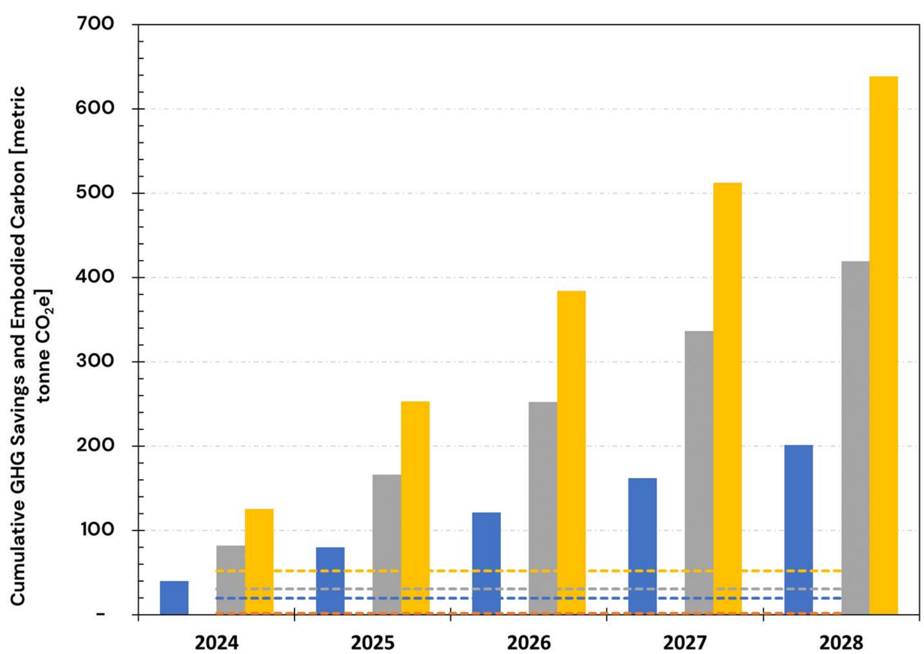

Figure A. 44: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using High RE Cost Electricity Emission Rates for CZ5 – Scenario 2: 100% Heat Pump Systems

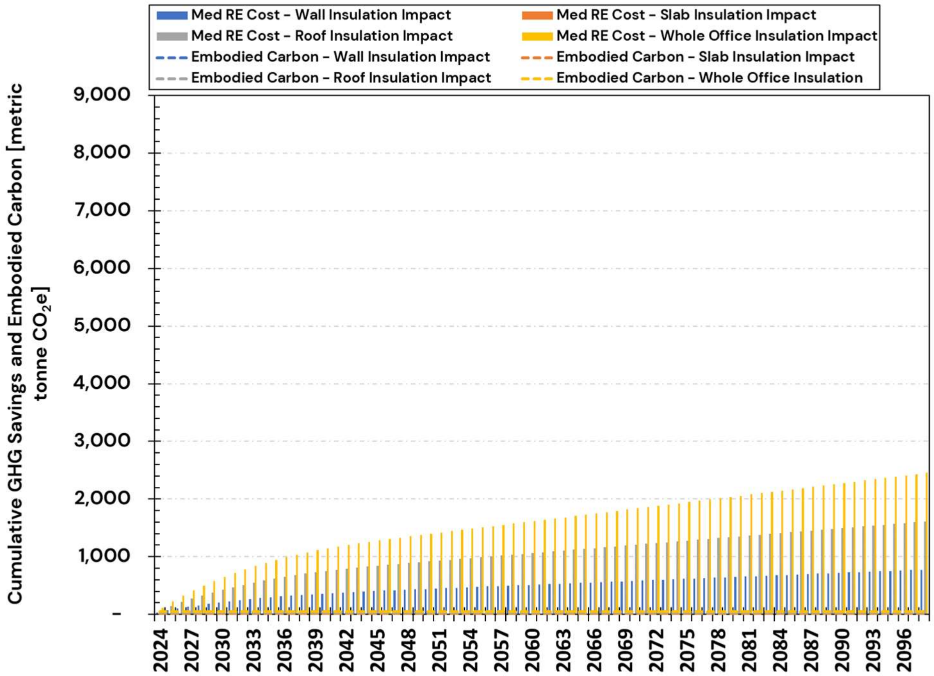

Figure A. 45: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using Medium RE Cost Electricity Emission Rates for CZ5 – Scenario 2: 100% Heat Pump Systems

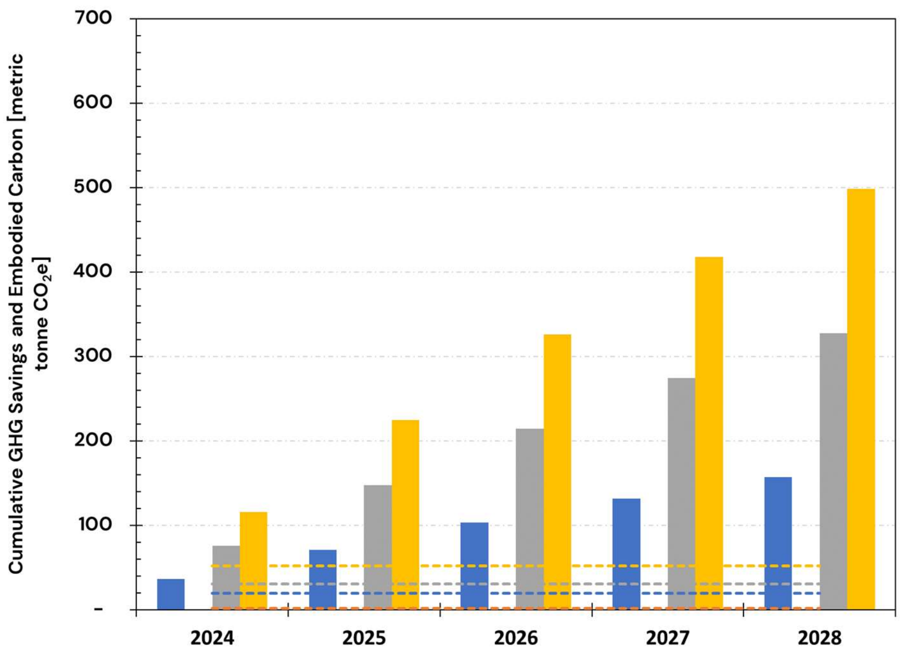

Figure A. 46: Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2028) Using Medium RE Cost Electricity Emission Rates for CZ5 – Scenario 2: 100% Heat Pump Systems

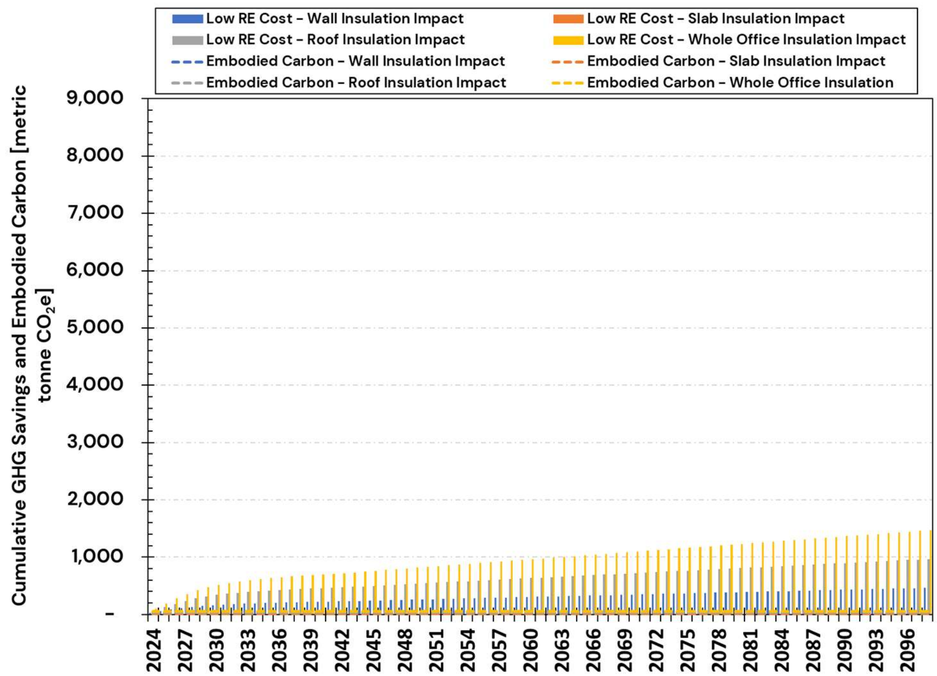

Figure A. 47: Embodied Carbon and Cumulative GHG Savings Over 75 Years (2024-2098) Using Low RE Cost Electricity Emission Rates for CZ5 – Scenario 2: 100% Heat Pump Systems

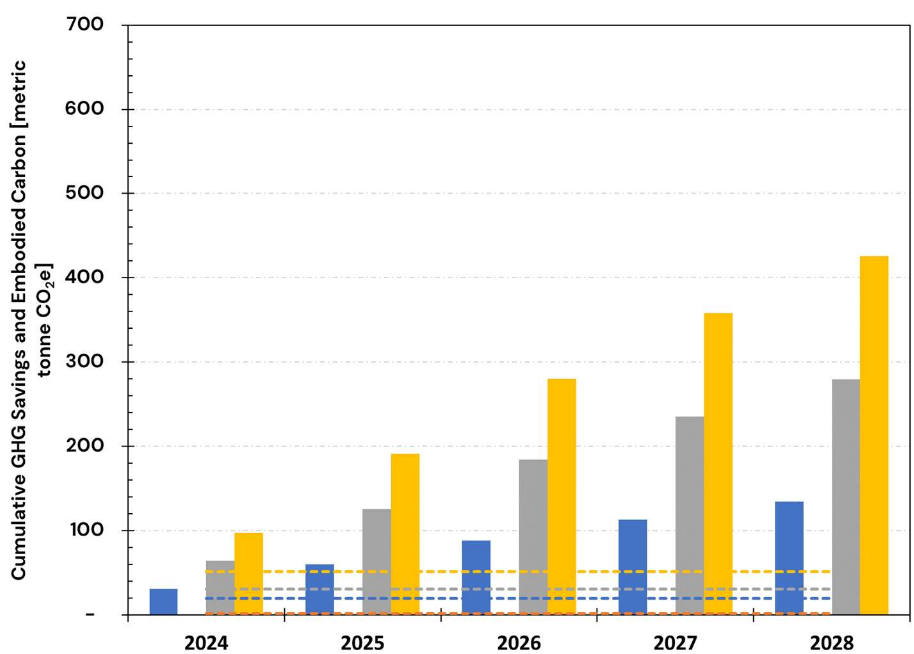

Figure A. 48:Embodied Carbon and Cumulative GHG Savings Over 5 Years (2024-2098) Using Low RE Cost Electricity Emission Rates for CZ5 – Scenario 2: 100% Heat Pump Systems